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AN INTEGRATED SIX-DEGREE-OF-FREEDOM TRAJECTORY AND AERODYNAMIC HEATING AND ABLATION COMPUTER PROGRAM

(STRAB-6)

W. J. Moulds

TECHNICAL REPORT NO. AFWL-TR-68-61

August 1968

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This research was performed under Program Element 6.24.05.06.F, Project 5791, Task 579122.

Inclusive dates of research were July 1966 through November 1967. This report was submitted by the Air Force Weapons Laboratory Project Officer, Mr. W. J. Moulds (WLDE), on 13 May 1968.

The author wishes to express his appreciation and thanks to Lt Colonel P. D. Cronquist and Mr. C. E. O'Haver for suggesting and encouraging the accomplishment of this work. Special thanks are due to Captain J. D. Young and Lt R. H. Aungier for their assistance and answers to the numerous questions by the author. Last, but not least, the author wishes to acknowledge the assistance of Mr. J. L. Hitchcock, who did much of the programing of STRAB-6.

This technical report has been reviewed and is approved.

W. J. MOULDS
Project Officer

PARLEY D. CRONQUIST
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Colonel, USAF
Chief, Development Division

ABSTRACT

(Distribution Limitation Statement No. 2)

An integrated computer program (STRAB-6) for the complete analysis of a blunt, conical reentry vehicle as to its trajectory and aerothermal environment upon atmospheric reentry is presented. The trajectory portion of the program calculates the vehicle motions in six-degrees-of-freedom, while the thermal portion calculates the aerodynamic heating and ablation of the vehicle. The earth model is an oblate, rotating spheroid whose parameters and gravitational potential are described herein. The equations of motion, the method of integration, thermal model and input forms for the program are discussed. The thermal model examined in this report assumes thick skin solution where the skin is of any composite structure made of discrete layers of material whose properties may vary from layer to layer. Also, the heatshield is comprised of one, two, or more different ablative materials. STRAB-6 computes nose-blunting and includes this effect in the aerodynamics. STRAB-6 is written in FORTRAN IV for the CDC 6600 computer.

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ILLUSTRATIONS

SECTION I

INTRODUCTION

The effects of aerodynamic heating and ablation on the motions, aerodynamic forces, and trajectory deviations of a reentry vehicle have been the subject of many analyses in recent years. Previous trajectory and heating programs have been separate, requiring that each be run separately with data from one used as input to the other. Such a method sometimes requires numerous runs before the output data converge to reasonable answers, and is both expensive in computer costs and time consuming. This report presents a computer program (STRAB-6) for the complete analysis of a reentry vehicle as to its trajectory and aerothermal environment. STRAB-6 provides a six-degree-of-freedom trajectory analysis as well as aerodynamic heating and ablation analysis for conical vehicles reentering the atmosphere at hypersonic speeds.

STRAB-6 uses some of the features from other 6-D programs (Refs. 1, 2, 3, 4, 5, 6). The trajectory portion of the program computes the six-degree-of-freedom rigid body motions for an aerodynamically symmetric reentry vehicle encountering a model atmosphere. Slender-body aerodynamic theory was used and the required aerodynamic coefficients are provided by subroutine inputs (as a function vehicle shape, angle-of-attack, and either Mach number or altitude). The atmospheric model that is used is based on the 1962 ARDC atmosphere, and the geocentric model that is used is a rotating oblate spheroid.

The aerodynamic heating and ablation portion of the program (Ref. 7) (HEATAB), in its original form, computed point mass heating for a sharp-nosed conical vehicle. The basic heating equations of this original program (HEATAB) are described in reference 7. There have been numerous improvements to the original program to include: heating on a blunt-nosed vehicle, the case where a vehicle heatshield is comprised of two or more different ablators, and boundary layer edge conditions.

The equations of motion and of heat transfer are general in that they apply to most axially symmetric vehicles. Even though this program considers the body in general motion under combined angles of attack and sideslip, the vehicle is assumed to ablate symmetrically. The ablation weight loss, nose bluntness, and vehicle volume changes are considered in the calculations for

the viscid and inviscid drag coefficients (CD) and stability derivatives, as well as the vehicle mass moment of inertia properties. In addition, the aerodynamic coefficients are calculated for the complete range of angle-of-attack ($0 \leq \alpha \leq 360°$) and sideslip ($0 \leq \beta \leq 360°$).

The position vector is calculated in a rotating earth-centered coordinate system, while the angular positions are calculated in a reentry-centered coordinate system. Computations are carried out, using the Runge-Kutta method of numerical integration employing a fixed step size-mode.

This program is specific in that the equations have been applied to a blunt-nosed conical vehicle with the starting point at reentry conditions. With some modifications, the user could easily adapt the program to analyze a missile from launch by adding thrust subroutines and substituting launch conditions for reentry conditions.

SECTION II

MAIN PROGRAM DESCRIPTION

1. GENERAL

The computer program, STRAB-6, is a self-contained program in the sense that it can generate the required aerodynamic data, and calculate the mass and inertial properties due to ablation changes of a symmetrical vehicle without any additional preliminary calculations.

STRAB-6 calculates the resultant loads, motions, and trajectory of a rigid vehicle in general 6-D motion as well as boundary-layer properties and time-temperature distribution in a body. If a nonablating trajectory is desired, an option is provided to omit the heating and ablation portion of the program.

At the initiation of a reentry run, the vehicle is located in space with the desired reentry conditions (i.e., velocity, flight path angle, altitude, roll rate). Also, the user must input the latitude, longitude, and azimuth at which he wishes to start the trajectory. Other trajectory parameters the user may wish to input are angle-of-attack and angle-of-sideslip; otherwise, these values are zero for a nominal trajectory.

The aerodynamic drag coefficients (CD) are obtained from Newtonian slender-body theory for inviscid drag and modified Blasius flat plate theory for viscous drag. These coefficients are calculated in subroutines CDSF and CDFM and are limited to vehicle shapes of spherically blunted cones where the ratio of base radius to axial length is approximately equal to the cone half-angle. A discussion of these theories is in section II-5.

The atmospheric model used in the program is based on the 1962 ARDC model atmosphere, and it expresses the density, ambient temperature, pressure, and the speed of sound as functions of altitude. The geocentric model used is a rotating oblate spheroid, where the sea level radius, R_E, is (figure 1)

$$R_E = \frac{R_{EQ}}{\left(1 + P_E \sin^2 \phi_c\right)^{1/2}} \tag{1}$$

where

R_{EQ} = earth equatorial radius-ft

λ_c = geocentric latitude-degree

$$P_E = \frac{e_E^2}{1 - e_E^2} = 0.00673852 \text{ (Ref 8)} \tag{2}$$

e_E = eccentricity of earth = 0.0818133302

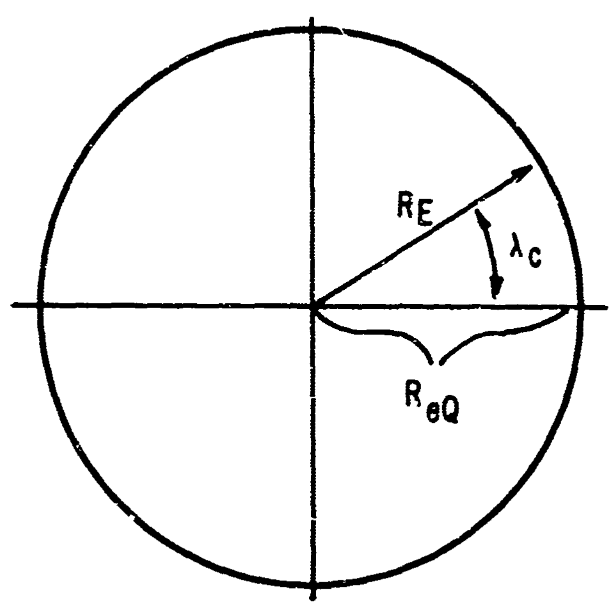


Figure 1. Geocentric Earth Model

The vehicle thermal model as presented in HEATAB has been modified to extend the calculations to include the total integrated ablation mass loss rate for a conical reentry vehicle. The body is divided into a number of segments, or stations along the cone, and the heating rate at each station is computed. In addition to the original input data required by HEATAB, the fore and aft radii, slant length, and transition Reynolds number of each body segment must be supplied. These input data are identified as: Data RS, Data RL, Data SOL, and Data RN. Computations of the skin temperature profile and ablation mass loss rate are identical to the method in HEATAB, except that these calculations are made for each X-station at each trajectory point.

As written, the STRAB-6 output will give, for each time interval, an output of trajectory conditions, body conditions, and aerodynamic parameters. The trajectory output conditions include time, altitude, velocity, and flight path angle. The body conditions for each X-station include weight loss rate per unit area, wall recession, and wall temperature profile. The aerodynamic parameters include CD, maximum aerodynamic load, angle-of-attack and sideslip, restoring forces and moments, and boundary layer edge conditions.

2. EQUATIONS OF MOTION

The equations of motion for an ascent or descent through the atmosphere can be written with various degrees of complexity. The equations differ in form depending upon the coordinate system, the number of degrees of freedom, the method of adjusting for the earth's rotation, and the integration scheme. In the evaluation of reentry vehicles for height-of-burst (HOB) errors, dispersion analysis, or circular error probable (CEP), the equations of motion must be written with six-degrees-of-freedom (6-D). This program employs a Runge-Kutta method of integration for a high degree of accuracy.

a. Coordinate Systems

The equations of motion can be written in vector notation using Newton's second law. A summation of the forces acting on the vehicle results in the equation

$$m \frac{d^2\vec{R}}{dt^2} = \sum \vec{F} - 2m\vec{\omega} \times \vec{v} - m\vec{\omega} \times (\vec{\omega} \times \vec{R})$$

Before this equation can be solved, however, it must be expressed in terms of a convenient coordinate system.

There are five principal coordinate systems or reference frames associated with orbital mechanics and trajectories. Various other reference frames can be used depending on the complexity of the problem to be solved. For this report, there are three reference frames: inertial reference frame, topocentric or horizontal reference frame, and earth reference frame. The following is a description of each and their interrelationships. All the reference frames are right-handed orthogonal coordinate systems.

(1) Inertial Reference Frame

The basic coordinate for the program is a nonrotating inertial reference frame fixed with its origin at the geocenter as shown in figure 2. Z_R points north along the axis of rotation of the earth and X_R and Y_R lie in the equatorial plane. X_R lies in the prime meridian plane at the start of a trajectory run (time, t = 0). The earth rotates with an angular velocity ω_E about Z_R; hence the earth reference frame, E, differs from the inertial frame, R, by a rotation $\omega_E t$.

The vehicle center of gravity (CG) is located in the inertial R frame by the longitude, β, latitude, λ_c, and vehicle altitude, ALT. The distance from the geocenter to the vehicle CG, measured along the vector whose orientation is determined by the angles β and λ_c is

$$R = R_E + ALT \qquad (3)$$

where R_E is defined by equation (1).

It may be worthwhile to digress briefly on the subject of latitude. There are three latitudes commonly used in astrodynamics; however, in this report we will be concerned only with geocentric and geodetic. Geocentric latitude, λ_c, is defined as the angle, measured at the earth's center, between the equatorial plane and a radius, R_E, to the point of interest on the earth's surface. The geodetic latitude, λ_g, is the angle between the equatorial plane and a normal to a reference spheroidal surface, Z_H, as shown in figure 3.

The reference spheroid is an oblate ellipsoid whose surface nearly approximates the sea-level surface of the earth. Such a spheroid is characterized by a "flattening" or "oblateness," f, where

$$f = (a - b)/a \qquad (4)$$

and a is the semimajor, and b the semiminor axis of the ellipse of revolution forming the spheroid. The derivation of equation (1) can be easily obtained from the equation for an ellipse if a equals equatorial radius, R_{EQ}, and b equals polar radius, R_{Po}. Therefore,

$$\frac{x^2}{R_{EQ}^{\;2}} + \frac{z^2}{R_{Po}^{\;2}} = 1 \qquad (5)$$

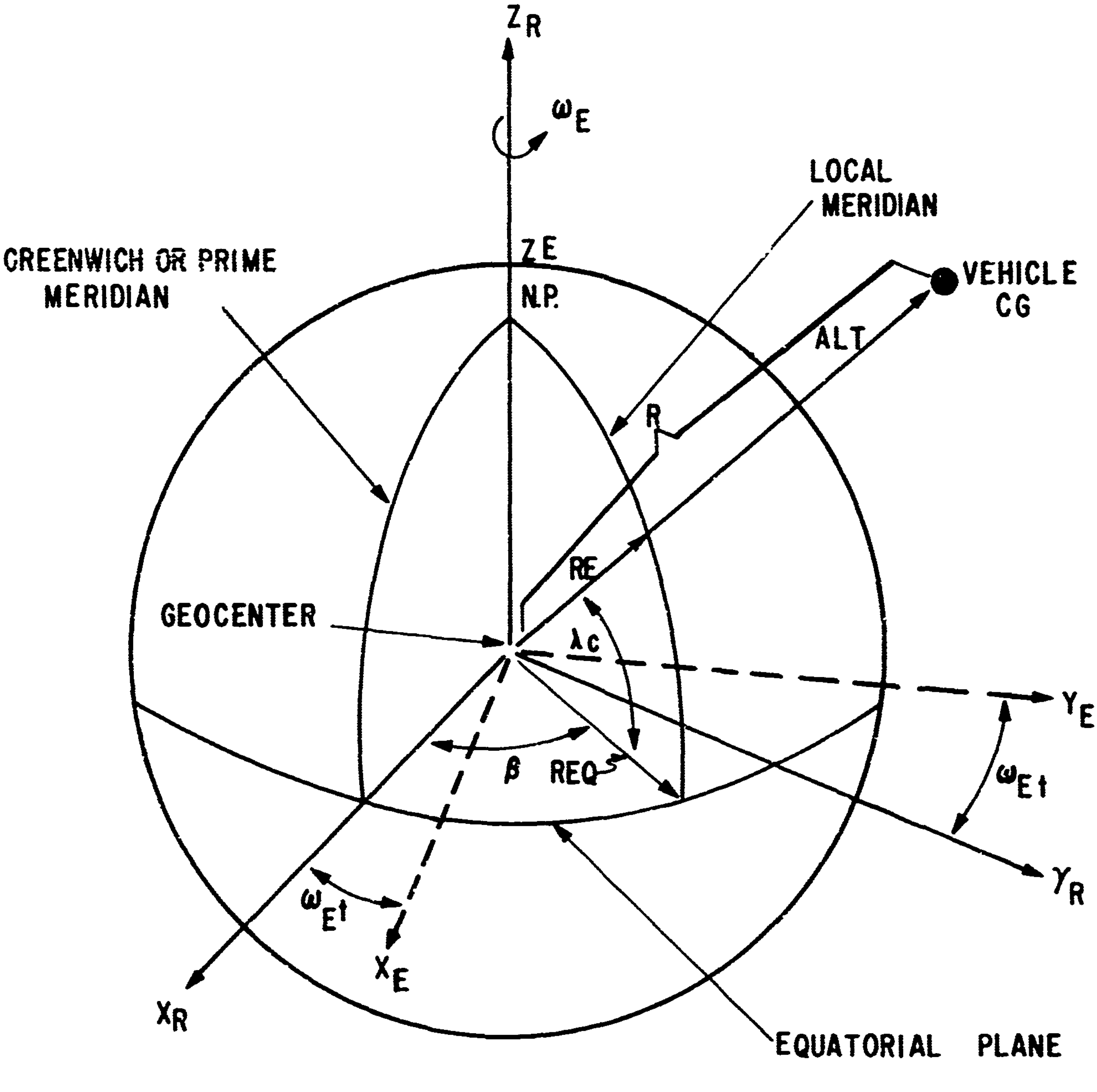


Figure 2. Inertial Reference Frame, R, and Earth Reference Frame, E

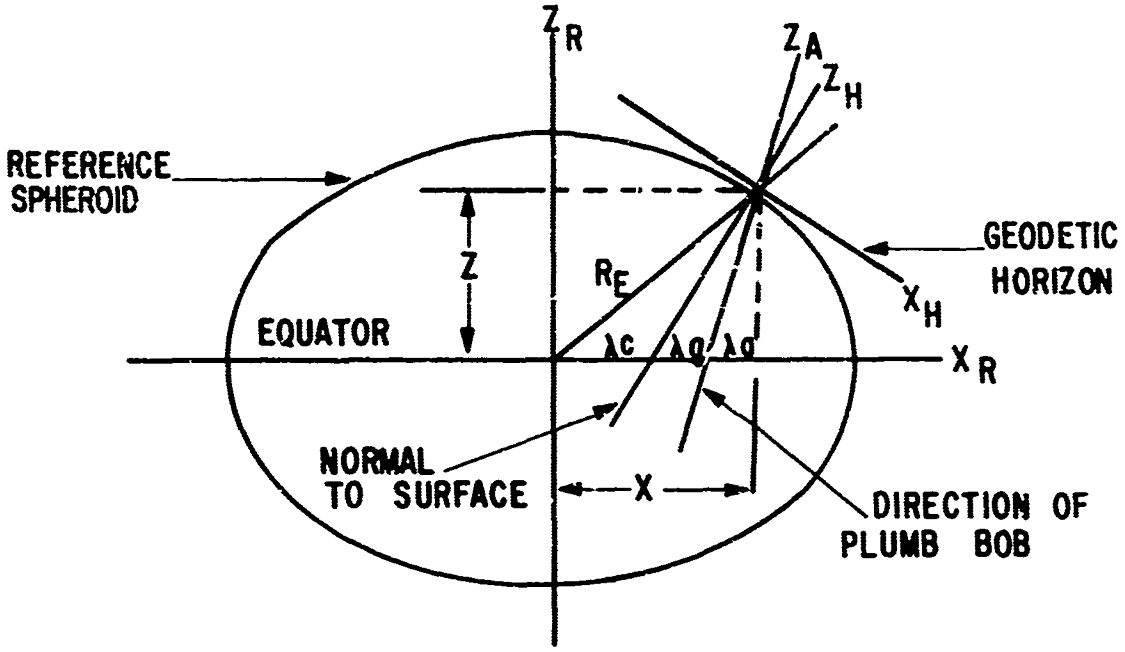


Figure 3. Geocentric, Geodetic, and Astronomical Latitudes (Ref. 9)

By multiplying ${R_{EQ}}^2$ and adding and subtracting z^2 on the left side,

$$x^2 + z^2 - z^2 + \frac{{R_{EQ}}^2 z^2}{{R_{Po}}^2} = {R_{EQ}}^2$$

But from figure 3

$$x^2 + z^2 = {R_E}^2$$

$$z = R_E \sin \lambda_c \qquad (6)$$

Therefore,

$$ {R_E}^2 + {R_E}^2 \sin^2 \lambda_c \left(\frac{{R_{EQ}}^2}{{R_{Po}}^2} - 1 \right) = {R_{EQ}}^2 \qquad (7)$$

Solving for R_E

$$R_E = \frac{R_{EQ}}{\left[1 + \sin^2 \lambda_c \left(\frac{R_{EQ}^2}{R_{Po}^2} - 1\right)\right]^{1/2}} \tag{8}$$

From reference 10

$$f = 1 - \sqrt{1 - e_E^2} \tag{9}$$

and from equation (4)

$$\frac{R_{EQ}}{R_{Po}} = \frac{1}{1 - f}$$

By squaring both sides and substituting equation (9) for f,

$$\frac{R_{EQ}^2}{R_{Po}^2} = \frac{1}{1 - e_E^2} \tag{10}$$

Now, by adding -1 to both sides,

$$\frac{R_{EQ}^2}{R_{Po}^2} - 1 = \frac{1}{1 - e_E^2} - 1 = \frac{e_E^2}{1 - e_E^2}$$

From equation (2), it is shown that

$$P_E = \frac{R_{EQ}^2}{R_{Po}^2} - 1 \tag{11}$$

Equation (1) is now obtained by substituting equation (11) into equation (8).

$$R_E = \frac{R_{EQ}}{\left(1 + P_E \sin^2 \lambda_c\right)^{1/2}}$$

The sea-level radius of the earth can now be determined at any station by knowing the geocentric latitude, λ_c, of the station.

The astronomical latitude, λ_a, is defined as the angle between the local astronomical zenith, Z_a, or vertical (as determined by a plumb bob or, actually, by the direction of the local gravitational field) and the equatorial plane. Since astronomical latitude is based upon the local gravitational field and is also centrifugal-force affected, it differs from the geodetic latitude by a very small value and can be considered negligible. Therefore, this report will consider geodetic and astronomical latitudes identical and will be concerned only with the relationship between geodetic and geocentric.

To convert from geodetic latitude to geocentric latitude, the slope (θ) of the tangent (geodetic horizon, see figure 4) at the station on the earth's surface can be obtained by differentiating equation (5).

$$\frac{2x}{R_{EQ}^{2}} + \frac{2z}{R_{Po}^{2}} \frac{dz}{dx} = 0$$

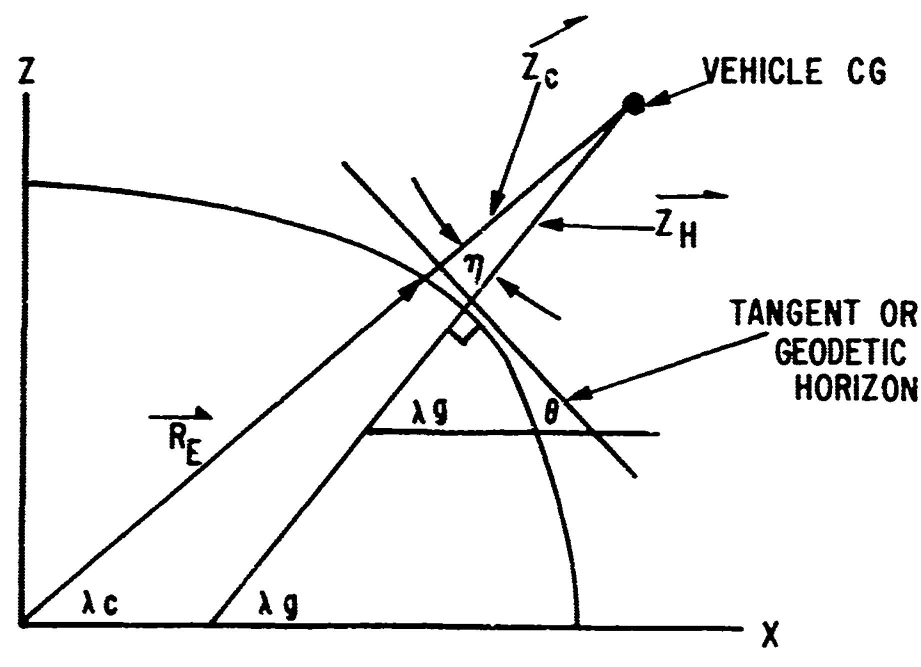


Figure 4. Geodetic to Geocentric

Therefore,

$$\tan\theta = \left|\frac{dz}{dx}\right| = \left| -\frac{R_{Po}^{2}}{R_{EQ}^{2}}\frac{x}{z}\right| \tag{12}$$

but

$$\tan\theta = \frac{1}{\tan\lambda_g}$$

$$\tan\lambda_c = \frac{z}{x}$$

By substituting these quantities into equation (12), the relationship between λ_g and λ_c is established.

$$\tan\lambda_g = \frac{R_{EQ}^{2}}{R_{Po}^{2}}\tan\lambda_c \tag{13a}$$

But by substituting equation (10) into equation (13a), λ_c can be determined from one constant. Therefore,

$$\lambda_c = \arctan\left[\left(1 - e_E^{2}\right)\tan\lambda_g\right] \tag{13b}$$

$$\eta = \lambda_g - \lambda_c \tag{14}$$

With the foregoing relationships established, the second reference frame can now be defined.

(2) Topocentric or Horizontal Reference Frame

The second of these coordinate systems is commonly known as the topocentric, but has other names depending upon the users application. Some of the names are horizon, launch, reentry, and trajectory system. This report refers to this coordinate system as the horizontal, H. The word topocentric

is derived from the Greek τόπος, meaning a place. In this reference frame, the origin is taken at the observer as shown in figure 5. The Y_H-axis is directed toward the east, the X_H-axis toward the south, and the Z_H-axis is directed toward the astronomical zenith. This system is rotated along with the earth's reference frame, and is, therefore, not inertial. The angle from the north direction measured clockwise (or east) in the X_H, Y_H plane is defined as azimuth, AZ.

With the horizontal reference frame now defined, it is now possible to complete three of the six-degrees-of-freedom.

b. Equation Development

Newton's second law for a rotating coordinate system is repeated here for convenience.

$$m \frac{d^2\vec{R}}{dt^2} = \sum \vec{F} - 2m\vec{\omega} \times \vec{v} - m\vec{\omega} \times (\vec{\omega} \times \vec{R})$$

or

$$\frac{d^2\vec{R}}{dt^2} = \frac{\sum \vec{F}}{m} - 2\left(\omega_E \times \frac{d\vec{R}}{dt}\right) - \vec{\omega}_E \times \left(\vec{\omega}_E \times \vec{R}\right) \qquad (15)$$

where

$\frac{d^2\vec{R}}{dt^2}$ is the vector acceleration of the vehicle CG with respect to the inertial reference frame

$\vec{F}$ is the total force vector on the reentry vehicle

$2\left(\vec{\omega}_E \times \frac{d\vec{R}}{dt}\right)$ is the coriolis acceleration of the axis system due to the rotation of the earth

m is vehicle mass

$\vec{\omega}_E \times \left(\vec{\omega}_E \times \vec{R}\right)$ is the centrifugal acceleration of the axis system due to the earth's rotation

$\omega_E = 0.7292 \times 10^{-4}$ radian/sec, earth rotational angular velocity

Since the horizontal reference system $\left(X_H, Y_H, Z_H\right)$ will rotate with the earth, several vector cross-products will appear in the final equation for $d^2\vec{R}/dt^2$. Therefore, the rotation rate vector, ω_E, and general vector, $\vec{R}$, must be expressed in the same reference frame $\left(X_H, Y_H, Z_H\right)$ for expansion.

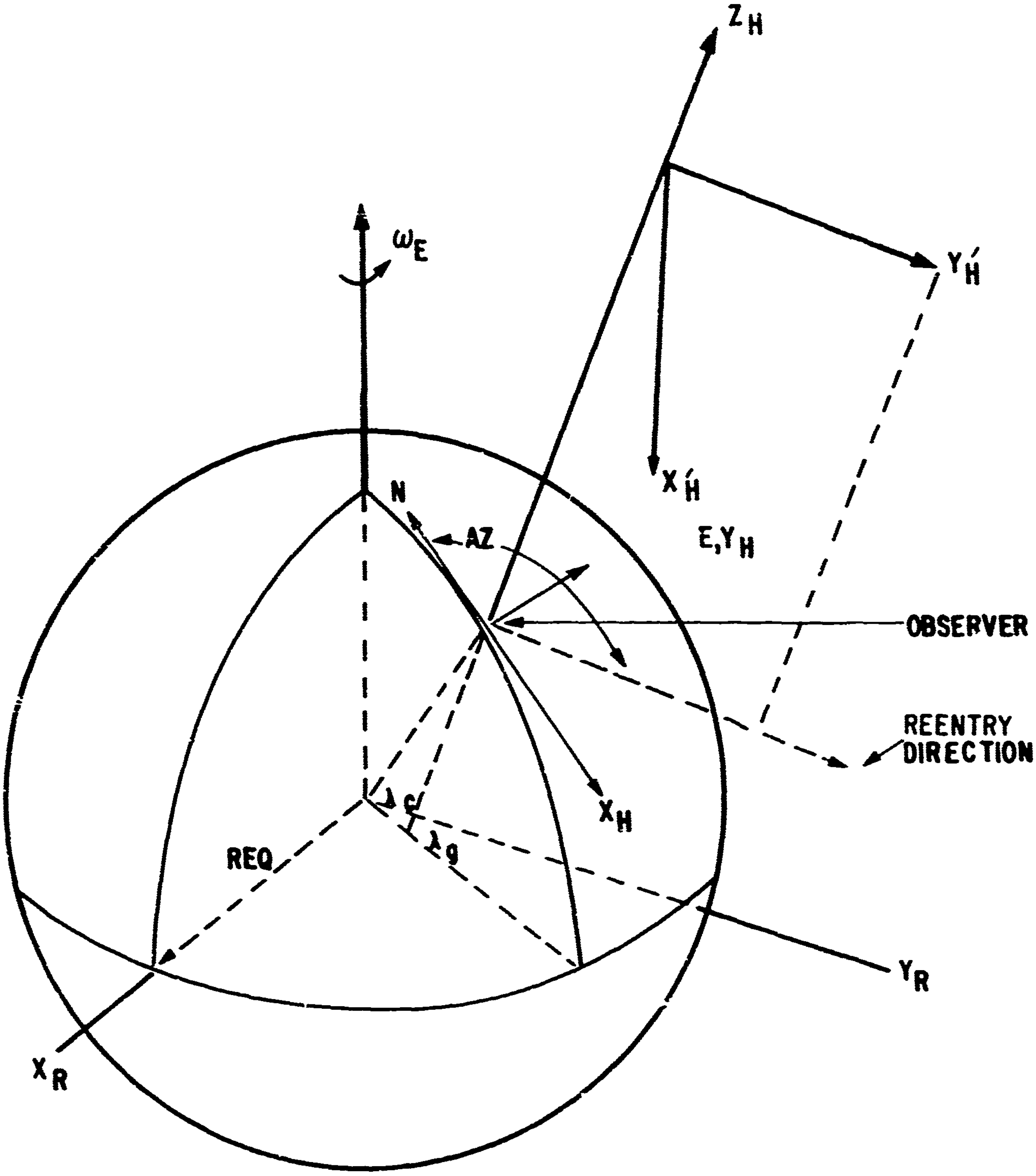


Figure 5. Horizontal Reference Frame

As shown in figure 5, pseudo-trajectory reference frame $\left(X_H', Y_H', Z_H'\right)$ has its origin at the initial position of the vehicle center of gravity. This frame is fixed in space (with respect to the horizontal (H) frame), with Z_H equal to the reentry altitude, and with X_H' and Y_H' rotated from X_H, Y_H about Z_H some initial azimuth angle, AZ. The vehicle flight path is initially fixed in the $Y_H' - Z_H'$ plane directed downward some reentry angle, γ_e.

Therefore, the components of X_H, Y_H, Z_H on X_H', Y_H', Z_H' is

$$\vec{X}_H' = \cos AZ \cdot \vec{X}_H + \sin AZ \cdot \vec{Y}_H \tag{16a}$$

$$\vec{Y}_H' = \sin AZ \cdot \vec{X}_H - \cos AZ \cdot \vec{Y}_H \tag{16b}$$

$$\vec{Z}_H' = \vec{Z}_H \tag{16c}$$

As previously shown, the horizontal reference frame is not inertial, and therefore, rotates at the same rotation rate as the earth. So that $\vec{\omega}_E$ may be written

$$\vec{\omega}_E = \omega_E \sin \lambda_g \, \vec{Z}_H - \omega_E \cos \lambda_g \, \vec{Y}_H \tag{17}$$

Equation (17) may be rewritten after substituting equation (16b) into equation (17).

$$\vec{\omega}_E = \omega_E \sin \lambda_g \, \vec{Z}_H - \omega_E \cos \lambda_g \cdot \sin AZ \, \vec{X}_Y$$

$$+ \omega_E \cos \lambda_g \cdot \cos AZ \, \vec{Y}_H \tag{18}$$

Therefore, the components of the earth's rotation rate in the horizontal reference frame may be written

$$\omega_{EX_H} = -\omega_E \cos \lambda_g \cdot \sin AZ \tag{19a}$$

$$\omega_{EY_H} = \omega_E \cos \lambda_g \cdot \cos AZ \tag{19b}$$

$$\omega_{EZ_H} = \omega_E \sin \lambda_g \tag{19c}$$

To determine the general vector, $\vec{R}$, and displacement accelerations, the vehicle CG must be considered displaced from the horizontal reference frame by the vector, $\vec{R}$, as shown in figure 6.

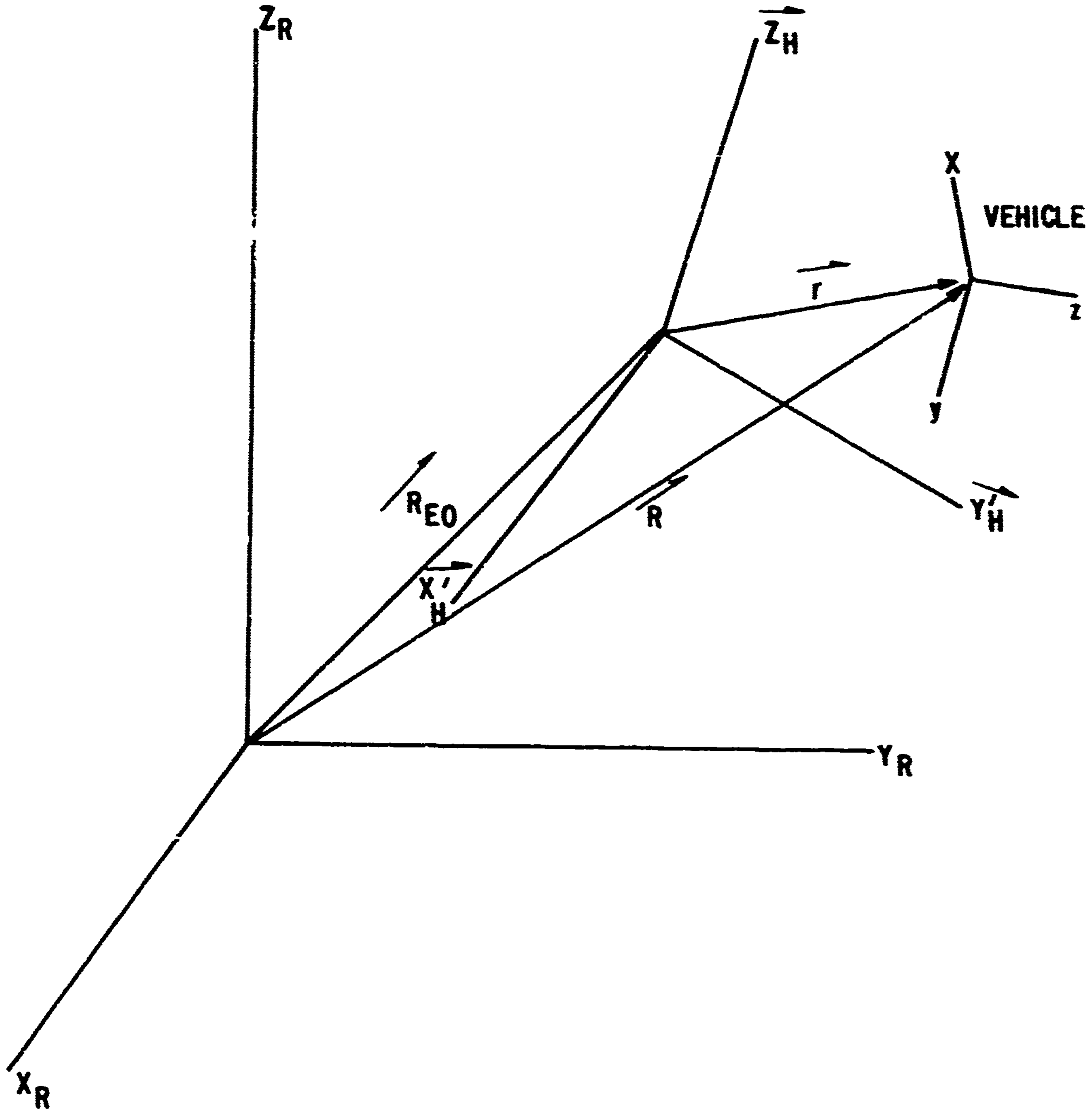


Figure 6. Inertial and Body Axis Coordinate Systems

From figure 6, the following relationship can be established:

$$\vec{R} = \vec{R}_{eo} + \vec{r} \tag{20}$$

$\vec{r}$ can be written in terms of its components on the horizontal reference frame as

$$\vec{r} = X\,\vec{X}'_H + Y\,\vec{Y}'_H + Z\,\vec{Z}_H \tag{21}$$

where X, Y, Z are the scalar vehicle CG displacement on the horizontal reference frame. $\vec{R}$ can now be written as

$$\vec{R} = X\,\vec{X}'_H + Y\,\vec{Y}'_H + Z\,\vec{Z}_H + \vec{R}_{eo} \tag{22}$$

Although $\vec{R}$ can be written in any reference frame, its vector components must be in the same reference frame. Therefore, the equation

$$\vec{R}_{eo} = R_{eo}\,\vec{Z}_c \tag{23}$$

must be written in terms of the horizontal reference system.

From figure 4, the vector, $\vec{Z}_c$, in the geocentric reference frame can be written in the form

$$\vec{Z}_c = \vec{Z}_H \cos\eta + \vec{Y}_H \cos\eta$$

or by substituting in equations (16b) and (16c), the following is obtained:

$$\vec{Z}_c = \vec{Z}_H \cos\eta + \vec{X}'_H \sin AZ \sin\eta - \vec{Y}'_H \cos AZ \sin\eta \tag{24}$$

Equation (23) can now be rewritten as

$$\vec{R}_{eo} = R_{eo} \sin AZ \sin\eta\,\vec{X}'_H - R_{eo} \cos AZ \sin\eta\,\vec{Y}'_H + R_{eo} \cos\eta\,Z_H \tag{25}$$

where components of R_{eo} in horizontal reference frame are

$$R_{XH} = R_{eo} \sin AZ \sin\eta$$

$$R_{YH} = -R_{eo} \cos AZ \sin\eta$$

$$R_{ZH} = R_{eo} \cos\eta \tag{26}$$

By substituting and collecting terms, the equation for $\vec{R}$ is

$$\vec{R} = \left(R_{xH} + X\right) \vec{X}'_H + \left(R_{yH} + Y\right) \vec{Y}'_H + \left(R_{zH} + Z\right) \vec{Z}_H \qquad (27)$$

The vectors $\vec{R}$ and $\vec{\omega}_E$ have now been expressed in the horizontal reference frame. The development of equation (15) can proceed further by taking the first derivative of R, with respect to time, in the following general form for an inertial coordinate system:

$$\left(\frac{d\vec{R}}{dt}\right) = \left[\frac{d\vec{R}}{dt}\right] + \vec{\omega} \times \vec{R}$$

where

$\left[\frac{d\vec{R}}{dt}\right]$ is the derivative relative to the rotating reference system

$\left(\frac{d\vec{R}}{dt}\right)$ is the vehicle CG velocity vector with respect to the inertial reference frame (R)

Therefore,

$$\frac{d\vec{R}}{dt} = \left(\dot{R}_{xH} + \dot{X}\right) \vec{X}'_H + \left(\dot{R}_{yH} + \dot{Y}\right) \vec{Y}'_H + \left(\dot{R}_{zH} + \dot{Z}\right) \vec{Z}_H$$

$$+ \vec{\omega}_E \times \left[\left(\dot{R}_{xH} + \dot{X}\right) \vec{X}'_H + \left(\dot{R}_{yH} + \dot{Y}\right) \vec{Y}'_H + \left(\dot{R}_{zH} + \dot{Z}\right) \vec{Z}_H\right] \qquad (28)$$

where a dot above the variable denotes first derivative with respect to time. The last term may be expanded in the following matrix form:

$$\vec{\omega}_E \times \vec{R} = \begin{vmatrix} \vec{X}'_H & \vec{Y}'_H & \vec{Z}'_H \\ \omega_{E_{xH}} & \omega_{E_{yH}} & \omega_{E_{zH}} \\ \left(R_{xH} + X\right) & \left(R_{yH} + Y\right) & \left(R_{zH} + Z\right) \end{vmatrix}$$

$$= \left[\omega_{E_{yH}} \left(R_{zH} + Z\right) - \omega_{E_{zH}} \left(R_{yH} + Y\right)\right] \vec{X}'_H + \left[\omega_{E_{zH}} \left(R_{xH} + X\right)\right.$$

$$\left. - \omega_{E_{xH}} \left(R_{zH} + Z\right)\right] \vec{Y}'_H + \left[\omega_{E_{xH}} \left(R_{yH} + Y\right) - \omega_{E_{yH}} \left(R_{xH} + X\right)\right] \vec{Z}_H$$

From this expanded form, the following equations can be established:

$$A = \omega_{E_{yH}} \left(R_{zH} + Z\right) - \omega_{E_{zH}} \left(R_{yH} + Y\right) \tag{29a}$$

$$B = \omega_{E_{zH}} \left(R_{xH} + X\right) - \omega_{E_{xH}} \left(R_{zH} + Z\right) \tag{29b}$$

$$C = \omega_{E_{xH}} \left(R_{yH} + Y\right) - \omega_{E_{yH}} \left(R_{xY} + X\right) \tag{29c}$$

Therefore, the velocity vector is

$$\frac{d\vec{R}}{dt} = (\dot{X} + A)\, \vec{X}_H' + (\dot{Y} + B)\, \vec{Y}_H' + (\dot{Z} + C)\, \vec{Z}_H \tag{30}$$

To obtain the acceleration, the second derivative of $\vec{R}$ with respect to time is taken

$$\frac{d^2\vec{R}}{dt^2} = (\ddot{X} + \dot{A})\, \vec{X}_H' + (\ddot{Y} + \dot{B})\, \vec{Y}_H' + (\ddot{Z} + \dot{C})\, \vec{Z}_H$$

$$+ \omega_E \, X \left[(\dot{X} + A)\, \vec{X}_H' + (\dot{Y} + B)\, \vec{Y}_H' + (\dot{Z} + C)\, \vec{Z}_H\right] \tag{31}$$

where $\dot{A}$, $\dot{B}$, $\dot{C}$ are the derivatives of equations (29a), (29b), and (29c),

$$\dot{A} = \omega_{E_{yH}} \dot{Z} - \omega_{E_{zH}} \dot{Y} \tag{32a}$$

$$\dot{B} = \omega_{E_{zH}} \dot{X} - \omega_{E_{xH}} \dot{Z} \tag{32b}$$

$$\dot{C} = \omega_{E_{xH}} \dot{Y} - \omega_{E_{yH}} \dot{X} \tag{32c}$$

and the last term is expanded to give

$$\vec{\omega}_E \times \frac{d\vec{R}}{dt} = \begin{vmatrix} \vec{X}'_H & \vec{Y}'_H & \vec{Z}'_H \\ \omega_{E_{xH}} & \omega_{E_{yH}} & \omega_{E_{zH}} \\ (\dot{X} + A) & (\dot{Y} + B) & (\dot{Z} + C) \end{vmatrix}$$

$$= \left[\omega_{E_{yH}} (\dot{Z} + C) - \omega_{E_{zH}} (\dot{Y} + B)\right] \vec{X}'_H$$

$$+ \left[\omega_{E_{zH}} (\dot{X} + A) - \omega_{E_{xH}} (\dot{Z} + C)\right] \vec{Y}'_H$$

$$+ \left[\omega_{E_{xH}} (\dot{Y} + B) - \omega_{E_{yH}} (\dot{X} + A)\right] \vec{Z}'_H$$

By substituting the above into equation (31), the following is obtained for the acceleration

$$\frac{d^2\vec{R}}{dt^2} = \left[\ddot{X} + \omega_{E_{yH}} \dot{Z} - \omega_{E_{zH}} \dot{Y} + \omega_{E_{yH}} (\dot{Z} + C) - \omega_{E_{zH}} (\dot{Y} + B)\right] \vec{X}'_H$$

$$+ \left[\ddot{Y} + \omega_{E_{zH}} \dot{X} - \omega_{E_{xH}} \dot{Z} + \omega_{E_{zH}} (\dot{X} + A) - \omega_{E_{xH}} (\dot{Z} + C)\right] \vec{Y}'_H$$

$$+ \left[\ddot{Z} + \omega_{E_{xH}} \dot{Y} - \omega_{E_{yH}} \dot{X} + \omega_{E_{xH}} (\dot{Y} + B) - \omega_{E_{yH}} (\dot{X} + A)\right] \vec{Z}'_H \quad (33)$$

By collecting terms and reducing equation (33), the final development of vehicle acceleration with respect to the horizontal reference frame is

$$\frac{d^2\vec{R}}{dt^2} = \left(\ddot{X} + 2\dot{A} + \omega_{E_{yH}} C - \omega_{E_{yH}} B\right) X'_H$$

$$+ \left(\ddot{Y} + 2\dot{B} + \omega_{E_{zH}} A - \omega_{E_{xH}} C \right) \vec{Y}_H'$$

$$+ \left(\ddot{Z} + 2\dot{C} + \omega_{E_{xH}} B - \omega_{E_{yH}} A \right) \vec{Z}_H \qquad (34)$$

or in component form in the horizontal reference frame,

$$a_x = \ddot{X} + 2\dot{A} + \omega_{E_{yH}} C - \omega_{E_{zH}} B \qquad (35a)$$

$$a_y = \ddot{Y} + 2\dot{B} + \omega_{E_{zH}} A - \omega_{E_{xH}} C \qquad (35b)$$

$$a_z = \ddot{Z} + 2\dot{C} + \omega_{E_{xH}} B - \omega_{E_{yH}} A \qquad (35c)$$

This completes the derivation of the acceleration equations, which includes coriolis and centripetal acceleration due to rotation of the coordinate system, and accelerations of the vehicle CG due to forces and moments.

To complete the equations of motion, it will be necessary to introduce the forces and moments acting on the vehicle. These forces and moments result mainly, for this program, from gravitational attraction, and from reaction of the air on the vehicle as a result of its motion. This is not to say other types of forces cannot be involved.

c. Earth Position Coordinates

Since the components of the gravitational force are dependent upon the position of the vehicle in the earth coordinate system, the instantaneous longitude and geocentric latitude can be obtained by the following method.

From equation (6) and reference 9, the geocentric latitude is

$$\lambda_c = \arcsin \frac{Z_E}{R_{EQ}}$$

and the longitude is

$$\beta = \arctan \frac{Y_E}{X_E}$$

where X_E, Y_E, and Z_E are coordinates in the earth reference system.

This program expresses the vehicle position in the horizontal reference frame; therefore, the position must be transformed to the earth reference frame. This can be done through examination of figures 2, 5, and 6, and the following transformation matrixes.

The order of transformation will be from X_H', Y_H', Z_H' to X_H, Y_H, and Z_H, to X_E, Y_E, and Z_E.

Therefore,

$$X_H = X_H' \sin AZ - Y_H' \cos AZ$$

$$Y_H = X_H' \cos AZ + Y_H' \sin AZ$$

$$Z_H = Z_H' \tag{36a}$$

or in matrix form

$$\begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix} = \begin{bmatrix} \sin AZ & (-\cos AZ) & 0 \\ \cos AZ & \sin AZ & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_H' \\ Y_H' \\ Z_H' \end{bmatrix} \tag{36b}$$

and

$$X_E = X_H \sin \lambda_g + Z_H \cos \lambda_g$$

$$Y_E = Y_H$$

$$Z_E = -X_H \cos \lambda_g + Z_H \sin \lambda g \tag{37a}$$

from which the following matrix is formed:

$$\begin{bmatrix} X_e \\ Y_e \\ Z_e \end{bmatrix} = \begin{bmatrix} \sin \lambda_g & 0 & \cos \lambda_g \\ 0 & 1 & 0 \\ -\cos \lambda_g & 0 & \sin \lambda_g \end{bmatrix} \cdot \begin{bmatrix} X_H \\ Y_H \\ Z_H \end{bmatrix} \tag{37b}$$

By substituting equation (36b) into equation (37b)

$$\begin{bmatrix} X_e \\ Y_e \\ Z_e \end{bmatrix} = \begin{bmatrix} \sin \lambda_g & 0 & \cos \lambda_g \\ 0 & 1 & 0 \\ -\cos \lambda_g & 0 & \sin \lambda_g \end{bmatrix} \cdot \begin{bmatrix} \sin AZ & (-\cos AZ) & 0 \\ \cos AZ & \sin AZ & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X'_H \\ Y'_H \\ Z'_H \end{bmatrix} \tag{38}$$

and expanding equation (38),

$$\begin{bmatrix} X_e \\ Y_e \\ Z_e \end{bmatrix} = \begin{bmatrix} \left(\sin \lambda_g \sin AZ\right) & \left(-\sin \lambda_g \cos AZ\right) & \cos \lambda_g \\ \cos AZ & \sin AZ & 0 \\ \left(-\cos \lambda_g \sin AZ\right) & \left(\cos \lambda_g \cos AZ\right) & \cos \lambda_g \end{bmatrix} \cdot \begin{bmatrix} X'_H \\ Y'_H \\ Z'_H \end{bmatrix} \tag{39}$$

From equation (39)

$$X_E = X'_H \left(\sin \lambda_g \sin AZ\right) - Y'_H \left(\sin \lambda_g \cos AZ\right) + Z'_H \cos \lambda_g \tag{40a}$$

$$Y_E = X'_H \cos AZ + Y'_H \sin AZ \tag{40b}$$

$$Z_E = -X'_H \left(\cos \lambda_g \sin AZ\right) + Y'_H \left(\cos \lambda_g \cos AZ\right) + Z'_H \sin \lambda_g \tag{40c}$$

where

$$X'_H = R_{xH} \div X$$

$$Y'_H = R_{yH} + Y$$

$$Z'_H = R_{zH} + Z$$

R_{xH}, R_{yH}, and R_{zH} are defined by equation (26). Therefore, the instantaneous geocentric latitude can be obtained from

$$\lambda_c = \arcsin\left(\frac{Z_E}{R}\right) \tag{41}$$

where

$$R = \left[\left(R_{xH} + X\right)^2 + \left(R_{yH} + Y\right)^2 + \left(R_{zH} + Z\right)^2\right]^{1/2}$$

since the earth is assumed to be a body of revolution about the polar axis, the instantaneous longitude may be defined as

$$\beta = \arctan\left(\frac{Y_E}{X_E}\right) \tag{42}$$

and will be considered positive when measured east from the prime meridian and negative when measured west.

d. Gravitational Equations

The potential function and equations used to obtain the gravitational forces to be included in the equations of motion are presented in this subsection. The gravitational potential of the earth is an expansion of spherical harmonics as a function of latitude and longitude. However, in this program, the earth is assumed to be a body of revolution so that the longitudinal effects may be ignored. Although some satellite data indicate that the earth's equator is elliptical where the major axis is somewhat larger than the minor axis, the difference though is very small compared to the equatorial radius.

The gravity components are determined by taking partial derivatives of the gravitational potential equation (Ref. 9).

$$\begin{aligned}\phi(R,\lambda) = \frac{-G_o M_o}{R}\Bigg[1 &+ \frac{J}{3}\left(\frac{R_{EQ}}{R}\right)^2\left(1 - 3\sin^2\lambda_c\right)\\ &+ \frac{H}{5}\left(\frac{R_{EQ}}{R}\right)^3\left(3\sin\lambda_c - 5\sin^3\lambda_c\right)\\ &+ \frac{K}{30}\left(\frac{R_{EQ}}{R}\right)^4\left(3 - 30\sin^2\lambda_c + 35\sin^4\lambda_c\right) + \dots\Bigg]\end{aligned} \tag{43}$$

where

$G_oM_o = 1.4076427 \times 10^{16}$ ft^3/sec^2 gravitational constant of the earth

R = radial distance to body CG from earth's geocenter

R_{EQ} = earth's equatorial radius

λ_c = geocentric latitude

$J = 1623.41 \times 10^{-6}$, coefficient of the second harmonic

$H = 6.04 \times 10^{-6}$, coefficient of the third harmonic

$K = 6.37 \times 10^{-6}$, coefficient of the fourth harmonic

The gravitational potential field is usually defined by spherical harmonics. Each higher order term in equation (43) is due to a deviation of the potential from that of a true sphere. Therefore, the potential is expressed as a series of Legendre polynomials in the variable, λ_c. Many analyses (Refs. 9, 11, 12) consider only the second-, third-, and fourth-order terms. The first harmonic $\left(R_{EQ}/R\right)$ is missing because of the choice of an equatorial coordinate system in which λ_c is measured relative to the center of the earth. The fifth harmonic is not sufficiently well known to justify its inclusion in this equation.

The gravitational acceleration of a vehicle along any line is the partial derivative of the potential function, ϕ, along that line. See figure 7.

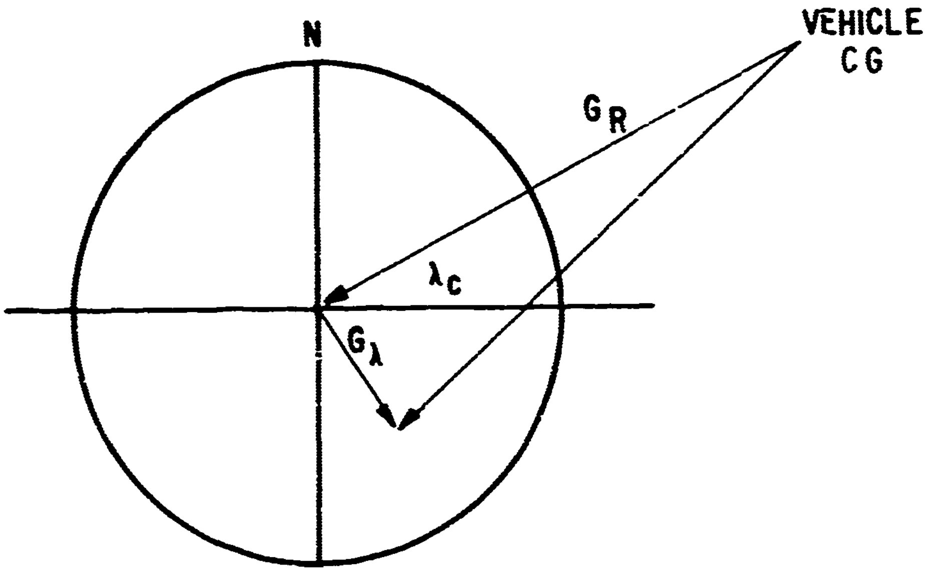


Figure 7. Gravitational Direction

$\vec{g}$ is related to $\Phi\left(R, \lambda_c\right)$ by

$$\vec{g} = -\nabla\Phi\left(R, \lambda_c\right)$$

where $\nabla\Phi$ is the gradient vector of $\Phi\left(R, \lambda_c\right)$. From figure 7, the force along the radius, R, is

$$G_r = mg_r = -m \frac{\partial\Phi\left(R, \lambda_c\right)}{\partial R}$$

and in R, λ_c direction

$$G_\lambda = mg_{\lambda c} = -\frac{m}{R}\frac{\partial\Phi\left(R, \lambda_c\right)}{\partial\lambda_c}$$

where m = mass of vehicle in slugs. From equation (43), G_R and $G\lambda_c$ are obtained.

$$G_R = -m\frac{\partial\Phi}{\partial R} = +m\, G_o M_o \left[-\frac{1}{R^2} - \frac{3J}{3}\left(\frac{R_{EQ}^{\;2}}{R^4}\right)\left(1 - 3\sin^2\lambda_c\right)\right.$$

$$- \frac{4}{5} H\left(\frac{R_{EQ}^{\;3}}{R^5}\right)\left(3\sin\lambda_c - 5\sin^3\lambda_c\right)$$

$$\left. - \frac{5K}{30}\left(\frac{R_{EQ}^{\;4}}{R^6}\right)\left(3 - 30\sin^2\lambda_c + 35\sin^4\lambda_c\right)\right]$$

$$G\lambda_c = -\frac{m}{R}\frac{\partial\Phi}{\partial\lambda_c} = \frac{+mG_oM_o}{R^2}\left[\frac{J}{3}\left(\frac{R_{EQ}^{\;2}}{R^2}\right)\left(-6\sin\lambda_c\cos\lambda_c\right)\right.$$

$$+ \frac{H}{5}\left(\frac{R_{EQ}^{\;3}}{R^3}\right)\left(3\cos\lambda_c - 15\sin^2\lambda_c\cos\lambda_c\right)$$

$$\left. + \frac{K}{30}\left(\frac{R_{EQ}^{\;4}}{R^4}\right)\left(-60\sin\lambda_c\cos\lambda_c + 140\sin^3\lambda_c\cos\lambda_c\right)\right]$$

simplifying and dividing through by m,

$$G_R = -\frac{G_o M_o}{R^2}\left[1 + J\left(\frac{R_{EQ}}{R}\right)^2\left(1 - 3\sin^2\lambda_c\right)\right.$$

$$+\frac{4H}{5}\left(\frac{R_{EQ}}{R}\right)^3\left(3\sin\lambda_c - 5\sin^3\lambda_c\right)$$

$$\left.+\frac{K}{6}\left(\frac{R_{EQ}}{R}\right)^4\left(3 - 30\sin^2\lambda_c + 35\sin^4\lambda_c\right)\right] \tag{44a}$$

$$G\lambda_c = -\frac{G_o M_o}{R^2}\left[-2J\left(\frac{R_{EQ}}{R}\right)^2\left(\sin\lambda_c\cos\lambda_c\right)\right.$$

$$+\frac{3H}{5}\left(\frac{R_{EQ}}{R}\right)^3\left(\cos\lambda_c - 5\sin^2\lambda_c\cos\lambda_c\right)$$

$$\left.+\frac{2K}{3}\left(\frac{R_{EQ}}{R}\right)^4\left(-3\sin\lambda_c\cos\lambda_c + 7\sin^3\lambda_c\cos\lambda_c\right)\right] \tag{44b}$$

Since G_R is along the radius $\vec{R}$ and $G\lambda_c$ is perpendicular to $\vec{R}$, they are in the inertial reference frame. For them to be included in the equations of motion, their components must be found with respect to the horizontal reference frame. This can be accomplished by the use of direction cosines and transformation matrices.

After examination of figure 8, the following series of equations can be written to transpose G_R and $G\lambda_c$ to the horizontal reference frame.

It is noted that G_R and $G\lambda$ are taken as positive in the direction shown in figures 7 and 8. Therefore, by definition

$$GR = +\frac{\partial\phi}{\partial R}$$

$$G\lambda = +\frac{1}{R}\frac{\partial\phi}{\partial R}$$

$$G\delta = 0 \tag{45}$$

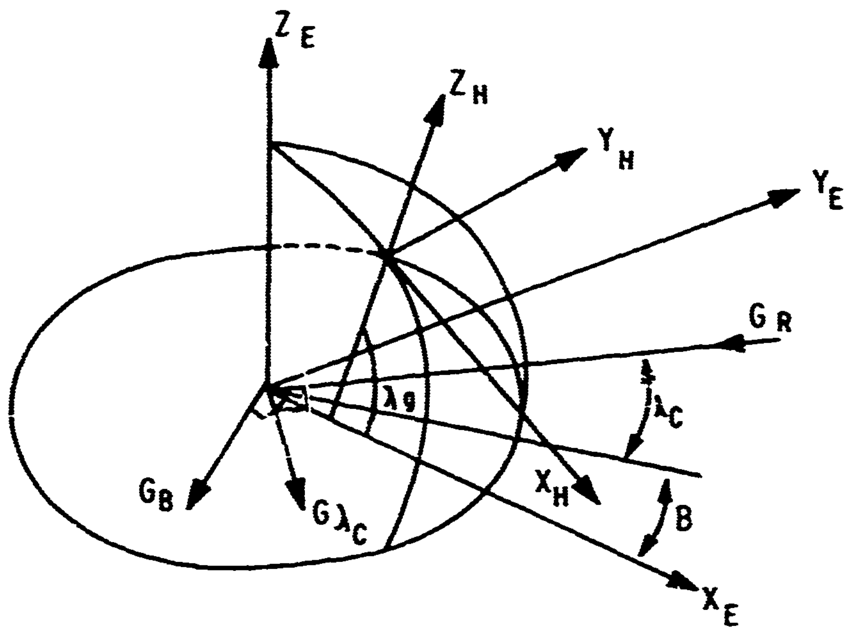


Figure 8. Gravitational Transformations

$$GX_E = -GR\left(\cos\lambda_c \cos\beta\right) + G\lambda\left(\sin\lambda_c \cos\beta\right) + G\beta \sin\beta$$

$$GY_E = -GR\left(\cos\lambda_c \sin\beta\right) + G\lambda\left(\sin\lambda_c \sin\beta\right) - G\beta \cos\beta$$

$$GZ_E = -GR \sin\lambda_c - G\lambda \cos\lambda_c \tag{46}$$

$$GX_H = GX_E \sin\lambda_g - GZ_E \cos\lambda_g$$

$$GY_H = GY_E$$

$$GZ_H = GX_E \cos\lambda_g + GZ_E \sin\lambda_g \tag{47}$$

From equations (16a), (16b), and (16c), the following is obtained:

$$GX'_H = GX_H \sin AZ + GY_H \cos AZ$$

$$GY'_H = -GX_H \cos AZ + GY_H \sin AZ$$

$$GZ'_H = GZ_H \tag{48}$$

Equations (46) and (47) can be expressed in matrix form

$$\begin{bmatrix} GX_H \\ GY_H \\ GZ_H \end{bmatrix} = \begin{bmatrix} \left(-\sin\lambda_g \cos\lambda_c \cos\beta + \cos\lambda_g \sin\lambda_c\right) & \left(\sin\lambda_g \sin\lambda_c \cos\beta + \cos\lambda_g \cos\lambda_c\right) & \left(\sin\lambda_g \sin\beta\right) \\ \left(-\cos\lambda_c \sin\beta\right) & \left(\sin\lambda_c \sin\beta\right) & (-\cos\beta) \\ \left(-\cos\lambda_g \cos\lambda_c \cos\beta - \sin\lambda_g \sin\lambda_c\right) & \left(\cos\lambda_g \sin\lambda_c \cos\beta - \sin\lambda_g \cos\lambda_c\right) & \left(\cos\lambda_g \sin\beta\right) \end{bmatrix} \cdot \begin{bmatrix} GR \\ G\lambda \\ G\beta \end{bmatrix} \qquad (49)$$

This matrix may be written into the following equations for transformation:

$$\begin{aligned} G11 &= -\sin\lambda_g \cos\lambda_c \cos\beta + \cos\lambda_g \sin\lambda_c \\ G12 &= \sin\lambda_g \sin\lambda_c \cos\beta + \cos\lambda_g \cos\lambda_c \\ G21 &= -\cos\lambda_c \sin\beta \\ G22 &= \sin\lambda_c \sin\beta \\ G31 &= -\cos\lambda_g \cos\lambda_c \cos\beta - \sin\lambda_g \sin\lambda_c \\ G32 &= +\cos\lambda_g \sin\lambda_c \cos\beta - \sin\lambda_g \cos\lambda_c \qquad (50) \end{aligned}$$

The final transformation is obtained by substituting equation (49) into equation (48).

$$\begin{aligned} GX'_H &= GR\ (G11 \cdot \sin AZ + G21 \cdot \cos AZ) \\ &\quad + G\lambda\ (G12 \cdot \sin AZ + G22 \cdot \cos AZ) \\ GY'_H &= GR\ (-G11 \cdot \cos AZ + G21 \cdot \sin AZ) \\ &\quad + G\lambda\ (-G12 \cdot \cos AZ + G22 \cdot \sin AZ) \\ GZ'_H &= GZ_H = GR\ (G31) + G\lambda\ (G32) \qquad (51) \end{aligned}$$

The components of the gravitational forces are now expressed in the horizontal reference frame and may be included with equations (35) to complete the equations of motion.

Before the aerodynamic forces and moments can be resolved, a method must be established for the transformation of components from the body reference frame to the horizontal reference frame and the inverse.

e. Euler Angles

Up to this point, only the equations for the three-translational degrees-of-freedom have been derived. This establishes the vehicle CG with respect to a horizontal reference system. To analyze the body forces and moments as a result of its motion about the CG, the angular orientation of the vehicle must be known with respect to the horizontal reference system.

The Euler angles describing the angular motion are ϕ, θ, and ψ, and will be noted as pitch, yaw, and roll angles, respectively. These angles are to be differentiated from the angles of attack and sideslip. The angles of attack and sideslip have a kinematic definition based on the components of the free-stream velocity relative to the body axes of the vehicle. The angular displacements, ϕ, θ, and ψ, on the other hand, are used to measure the vehicle attitude with respect to a fixed set of axes (X, Y, and Z), and in no way require motion of the vehicle relative to the surrounding air for their definition.

Consider a vehicle moving with respect to the inertial axes X, Y, and Z which are also fixed in space. The following will describe one of several ways of specifying the angular orientation of a vehicle at any instant of time. This will be done by successively pitching, yawing, and rolling the X, Y, and Z axes until they coincide with the axes x, y, and z of the vehicle as shown in figure 9.

First, pitch the vehicle by an angular displacement ϕ around OX so that Z goes to Z_1 and Y goes to Y_1 (figure 9a). The relationship between the two coordinate systems is then given by the following transfer matrix:

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (52)$$

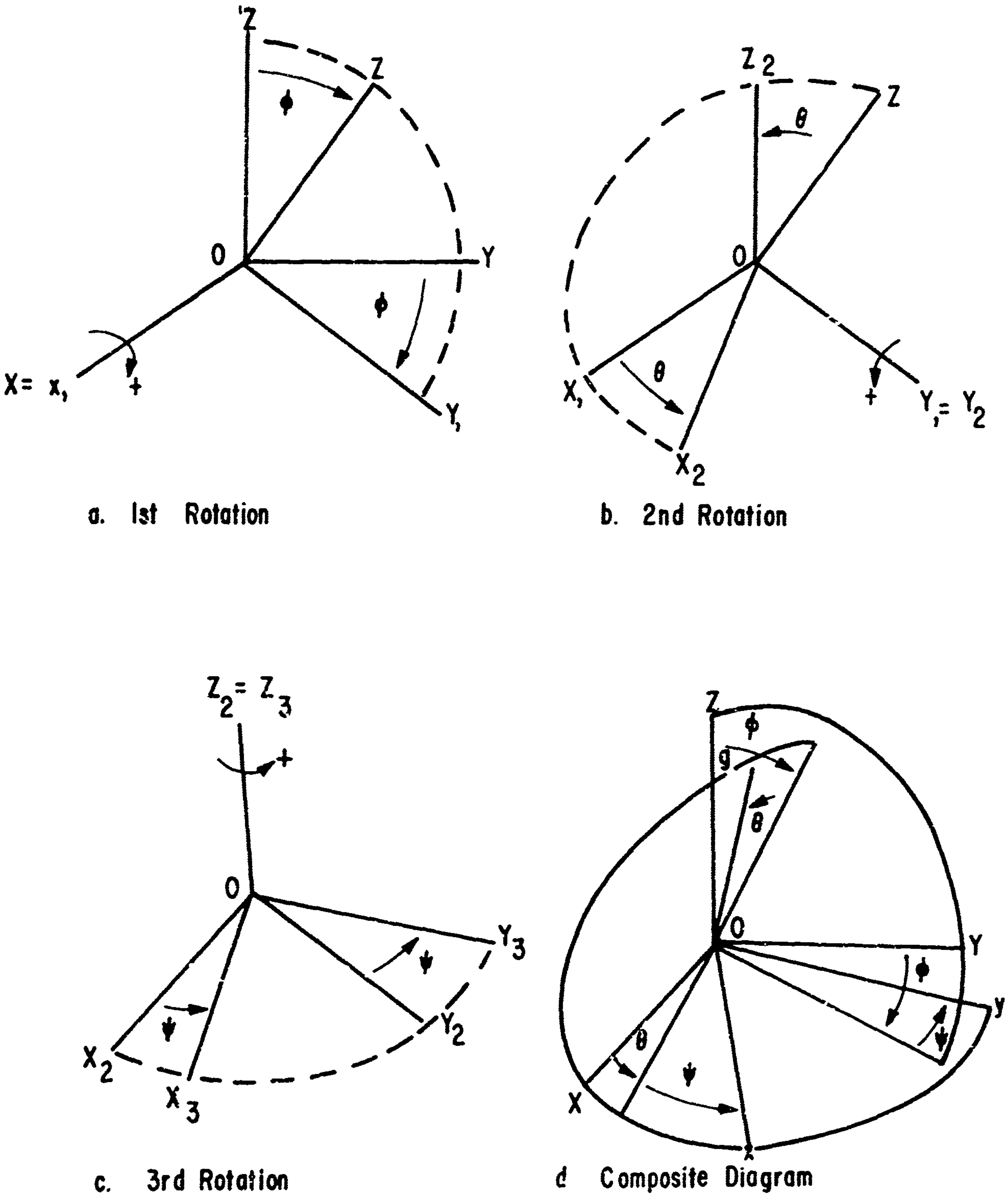


Figure 9. System of Angular Displacements

Next, yaw the vehicle by an angle θ about the OY_1 axes so that X_1 goes to X_2 and Z_1 to Z_2 (figure 9b). The new relationship is given by the transfer matrix

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \tag{53}$$

Finally, roll the vehicle by angle ψ around the OZ_2 axis so that X_2 moves to X_3, and Y_2 to Y_3 (figure 9c). The transfer matrix for this rotation is

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} \tag{54}$$

where

$$x = X_3$$
$$y = Y_3$$
$$z = Z_3$$

The operations of pitch, yaw, and roll for this program must always be performed in this order since angular displacements do not follow the ordinary laws of vector addition, but, in fact, follow a noncommutative law. Under this system of rotations, the direction cosines of the finial vehicle axes x, y, and z to the fixed axis X, Y, and Z are obtained by substituting equation (52) into equations (53).

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & (-\sin\theta\sin\phi) & (-\sin\theta\cos\phi) \\ 0 & \cos\phi & -\sin\phi \\ \sin\theta & (\sin\phi\cos\theta) & (\cos\phi\cos\theta) \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{55}$$

Then substitute equation (54) into equation (55)

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (\cos\psi\cos\theta) & (-\sin\theta\sin\phi\cos\psi + \sin\psi\cos\theta) & (-\sin\theta\cos\phi\cos\psi - \sin\psi\sin\phi) \\ (-\sin\psi\cos\theta) & (\sin\theta\sin\phi\sin\psi + \cos\psi\cos\phi) & (\sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi) \\ \sin\theta & (\cos\theta\sin\phi) & (\cos\theta\cos\phi) \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{56}$$

Therefore, equation (56) will transform components from the fixed axes or horizontal reference system to the vehicle or body reference system. To transform components from the vehicle axes to the horizontal references axes, the matrix of equation (56) must be inverted by interchanging rows and columns. The elements of equation (56) may be written for simplicity as follows, where subscripts indicate rows and columns.

$$\begin{aligned}
A_{11} &= \cos\theta\cos\psi \\
A_{12} &= -\sin\theta\sin\phi\cos\psi + \sin\psi\cos\theta \\
A_{13} &= -\sin\theta\cos\phi\cos\psi - \sin\psi\sin\phi \\
A_{21} &= -\sin\psi\cos\theta \\
A_{22} &= \sin\theta\sin\phi\sin\psi + \cos\psi\cos\phi \\
A_{23} &= \sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi \\
A_{31} &= \sin\theta \\
A_{32} &= \cos\theta\sin\phi \\
A_{33} & \cos\theta\cos\phi
\end{aligned} \tag{57}$$

f. Transformation of Angular Velocities

It is now necessary to express the angular velocities ω_x, ω_y, and ω_z with respect to the vehicle axes in terms of the Euler angles.

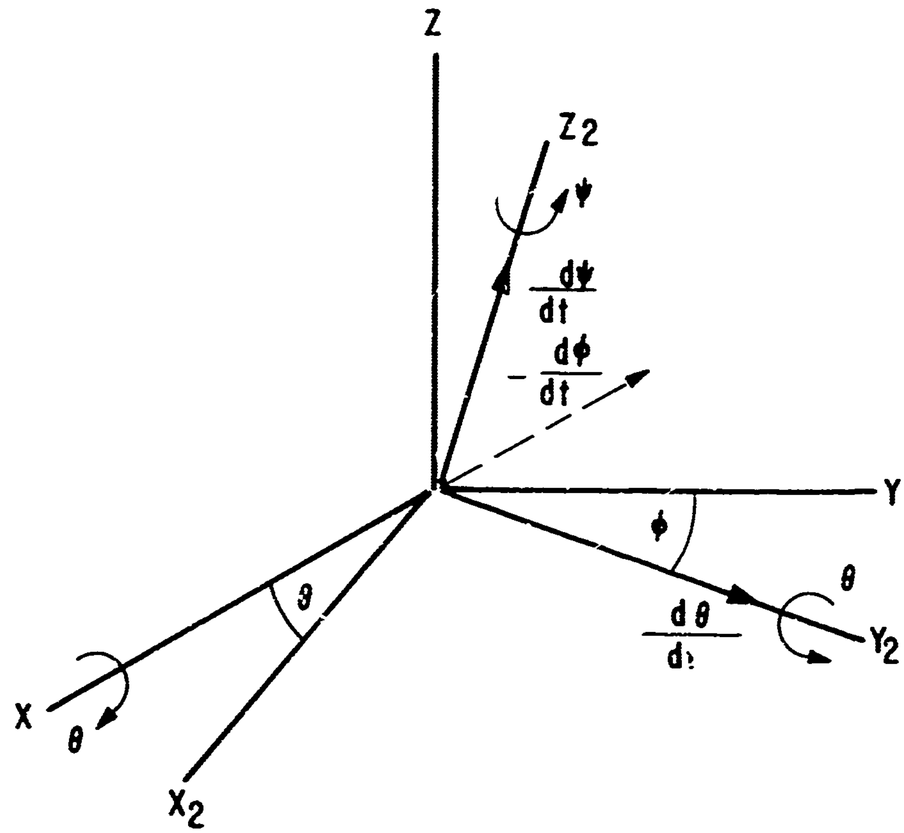


Figure 10. Angular Velocities of Euler Angles

The components of the angular velocities along the X_2, Y_2, and Z_2 axes to the vehicle axes x, y, and z shown in figure 10 are

$$\omega_x = \frac{-d\phi}{dt}\cos\theta\cos\psi + \frac{d\theta}{dt}\sin\psi$$

$$\omega_y = \frac{d\phi}{dt}\cos\theta\sin\psi + \frac{d\theta}{dt}\cos\psi$$

$$\omega_z = \frac{-d\phi}{dt}\sin\theta + \frac{d\psi}{dt} \qquad (58)$$

The equations in section II-2e and equation (56) have been derived with respect to the inertial axes X, Y, and Z. If the axes system is allowed to rotate, the angular velocity of the earth ω_E must be included. Therefore, the inertial angular rates of the vehicle are

$$\Omega_x = \omega_X + \omega_{E_{XH}}$$

$$\Omega_y = \omega_Y + \omega_{E_{YH}}$$

$$\Omega_z = \omega_Z + \omega_{E_{ZH}} \tag{59}$$

where $\omega_{E_{xH}}$, $\omega_{E_{yH}}$, and $\omega_{E_{zH}}$ are defined by equation (19). These are the components of the earth's rotation rate in the horizontal reference frame.

Since this program was written for a symmetrical cone with uniform weight distribution and further assumes symmetrical ablation, then the products of inertia will be zero regardless of roll angle, ψ. (This will be shown in section II-2g.) Therefore, the roll and transverse moment of inertia can be obtained independent of ψ. This will simplify the equations and allow the angular momentum, $\vec{h}_o$, to be written in the second rotation.

Therefore, equation (58) can be simplified and written in the X_2, Y_2, and Z_2 axes as

$$\omega_{x2} = -\frac{d\phi}{dt}\cos\theta$$

$$\omega_{y2} = \frac{d\theta}{dt}$$

$$\omega_{z2} = -\frac{d\phi}{dt}\sin\theta + \frac{d\psi}{dt} \tag{60}$$

which are the total rotation rates of the vehicle in the second rotated axes.

Now $\omega_{E_{xH}}$, $\omega_{E_{yH}}$, and $\omega_{E_{zH}}$ must also be written in the same axes system as the vehicle angular rates. This can be done by using the transformation equation (55), which will result in

$$\omega_{E_{x_2}} = \omega_{E_{x_H}}\cos\theta - \omega_{E_{y_H}}\sin\theta\sin\phi - \omega_{E_{z_H}}\sin\theta\cos\phi$$

$$\omega_{E_{y_2}} = 0 + \omega_{E_{y_H}}\cos\phi - \omega_{E_{z_H}}\sin\phi$$

$$\omega_{E_{z_2}} = \omega_{E_{x_H}}\sin\theta + \omega_{E_{y_H}}\sin\phi\cos\theta + \omega_{E_{z_H}}\cos\phi\cos\theta \tag{61}$$

Therefore, equation (59) can be written as

$$\Omega_x = \omega_{x_2} + \omega_{Ex_2}$$

$$\Omega_y = \omega_{y_2} + \omega_{Ey_2}$$

$$\Omega_z = \omega_{z_2} + \omega_{Ez_2} \tag{62}$$

which are the inertial angular velocities of the vehicle in the X_2, Y_2, and Z_2 axes.

Since equation (62) is written in the second rotated axes system, it is also necessary to have the angular velocity of that coordinate system. Therefore,

$$\Omega_{x_2} = -\frac{d\psi}{dt}\cos\theta + \omega_{E_{X_2}}$$

$$\Omega_{y_2} = \frac{d\theta}{dt} + \omega_{E_{Y_2}}$$

$$\Omega_{z_2} = -\frac{d\psi}{dt}\sin\theta + \omega_{E_{Z_2}} \tag{63}$$

which completes the transformation of angular velocities.

g. Moment of Momentum

A particle of mass, m, moving with velocity, $\dot{\vec{R}}$, figure 11, has a linear momentum (Ref. 13)

$$\vec{P} = m\,\dot{\vec{R}}$$

The moment of this linear momentum about an arbitrary point, O, is defined as

$$\vec{h}_o = \vec{r} \times m\,\dot{\vec{R}} \tag{64}$$

where

$\dot{\vec{R}}$ = absolute velocity of m

$\vec{r}$ = radius drawn from O as shown in figure 11

$\vec{h}_o$ = the angular momentum of the particle about the point O

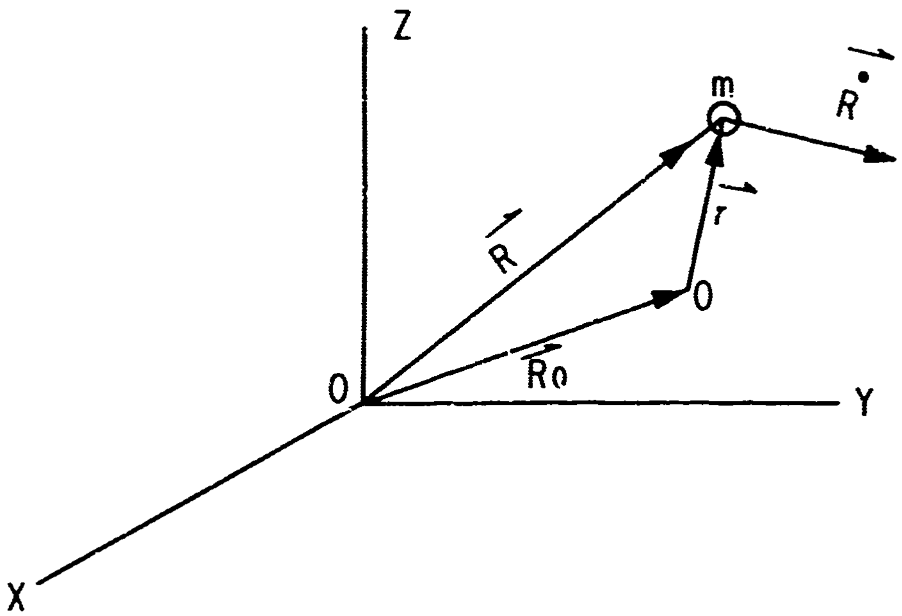


Figure 11. Moment of Momentum about 0

The angular momentum of a rigid body, figure 12, about any axis perpendicular to the plane of motion and passing through the point 0 fixed in a moving body is the sum of the moments of the linear momenta of all its particles about the axis. Therefore, equation (64) can be rewritten as

$$\vec{h}_o = \sum_i \vec{r}_i \times m \vec{v}_i$$

where $\vec{v}_i$ = velocity of any point i on the body. The velocity of a representative particle of mass m_i may be expressed in terms of the velocity of 0 plus the velocity of m_i with respect to 0.

$$\vec{v}_i = \vec{v}_o + \vec{\omega} \times \vec{r}_i$$

Therefore,

$$\vec{h}_o = \sum_i \vec{r}_i \times m_i \left(\vec{v}_o + \vec{\omega} \times \vec{r}_i\right)$$

or is expanded from

$$\vec{h}_o = \sum_i \vec{r}_i \times \left(\vec{\omega} \times \vec{r}_i\right) m_i - \vec{v}_o \times \sum_i m_i \vec{r}_i$$

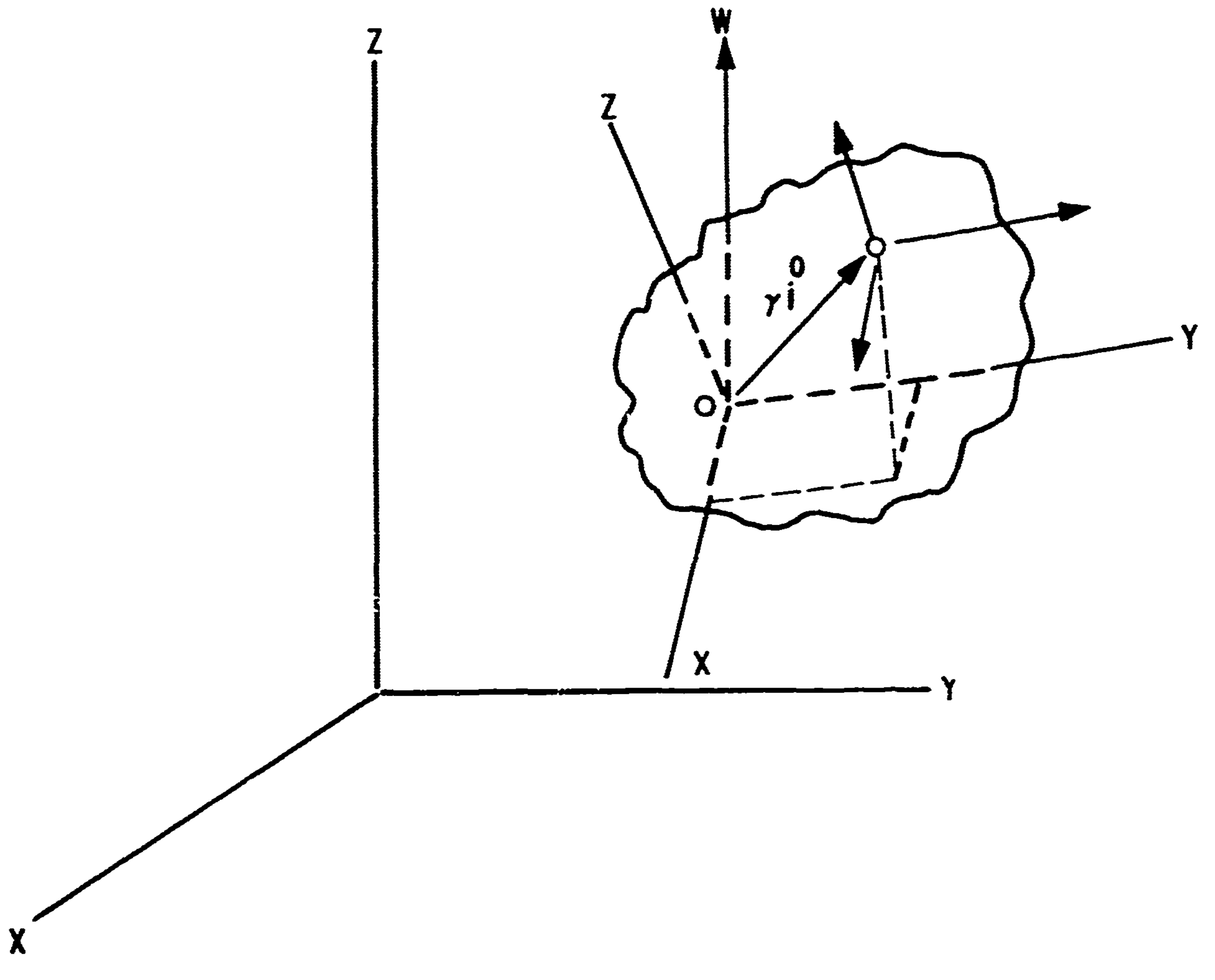


Figure 12. Components of Momentum

If, by definition, 0 coincides with the center of mass, the term $\sum_i m_i \dot{r}_i$ is equal to zero, the angular momentum can be expressed by the following integral

$$\vec{h}_o = \int \vec{r} \times (\vec{\omega} \times \vec{r})\, dm \tag{65}$$

The relation between the angular momentum of a body and the applied moments, $\vec{M}_o$, of the forces $\sum \vec{F} = m\ddot{\vec{R}}$ acting on m is obtained from rotational equation of motion.

$$\vec{M}_o = \sum \vec{r} \times m\ddot{\vec{R}} \tag{66}$$

Taking the second derivative of the expression

$$\vec{R} = \vec{R}_o + \vec{r}$$

and substituting into equation (66)

$$\vec{M}_o = \sum \vec{r} \times m\left(\ddot{\vec{R}}_o + \ddot{\vec{r}}\right)$$

or

$$\vec{M}_o = \sum \frac{d}{dt}(\vec{r} \times m\,\dot{\vec{r}}) - \ddot{\vec{R}}_o \times \sum m\vec{r} \qquad (67)$$

Again $\sum mr = 0$ when 0 coincides with center of mass. Equation (67) reduces to

$$\vec{M}_o = \sum \frac{d}{dt}(\vec{r} \times m\,\dot{\vec{r}}) \qquad (68)$$

but $\dot{\vec{r}}$ is equal to the following:

$$\dot{\vec{r}} = \left(\frac{d\vec{r}}{dt}\right) = \left[\frac{d\vec{r}}{dt}\right] + \vec{\omega} \times \vec{r}$$

where

$\left(\frac{d\vec{r}}{dt}\right)$ = total derivative relative to inertial axis

$\left[\frac{d\vec{r}}{dt}\right]$ = derivative relative to rotating axis and, since body is rigid, is equal to zero

Therefore,

$$\dot{\vec{r}} = \vec{\omega} \times \vec{r}$$

and substituting into equation (67) the relationship between $\vec{M}_o$ and $\dot{\vec{h}}_o$ is established.

$$\vec{M}_o = \frac{d}{dt}\left(\vec{r} \times m\,(\vec{\omega} \times \vec{r})\right) \qquad (69)$$

or

$$\vec{M}_o = \frac{d\,\vec{h}_o}{dt} \tag{70}$$

With this relationship established, the derivation of $\vec{h}_o$ can be continued. The integral in equation (65) must be evaluated and this is done by first expanding the cross product $\vec{\omega} \times \vec{r}$

$$\vec{\omega} \times \vec{r} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \Omega_x & \Omega_y & \Omega_z \\ x & y & z \end{vmatrix} = \left(\Omega_y z - \Omega_z y\right) \vec{i} + \left(\Omega_z x - \Omega_x z\right) \vec{j} + \left(\Omega_x y - \Omega_y x\right) \vec{k} \tag{71}$$

where Ω_x, Ω_y, and Ω_z is defined by equation (62). Then expansion of the cross product $\vec{r} \times (\vec{\omega} \times \vec{r})$ is

$$\vec{r} \times (\vec{\omega} \times \vec{r}) = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x & y & z \\ \left(\Omega_y z - \Omega_z y\right) & \left(\Omega_z x - \Omega_x z\right) & \left(\Omega_x y - \Omega_y x\right) \end{vmatrix}$$

$$\begin{aligned} &= \vec{i}\left[\Omega_x\,(y^2 + z^2) - \Omega_y\,(xy) - \Omega_z\,(xz)\right] dm \\ &+ \vec{j}\left[-\Omega_x\,(xy) + \Omega_y\,(x^2 + z^2) - \Omega_z\,(yz)\right] dm \\ &+ \vec{k}\left[-\Omega_x\,(xz) + \Omega_y\,(yz) + \Omega_z\,(x^2 + y^2)\right] dm \end{aligned} \tag{72}$$

By definition, the moments of inertia of a body about the x, y, z axes are

$$I_x = \int (y^2 + z^2)\,dm$$

$$I_y = \int (x^2 + z^2)\,dm$$

$$I_z = \int (x^2 + y^2)\,dm$$

and the products of inertia are

$$I_{xy} = \int xy\ dm$$

$$I_{xz} = \int xz\ dm$$

$$I_{yz} = \int yz\ dm$$

If the x, y, z axes are considered the principal axes, the products of inertia and the time derivatives of the moments of inertia are zero.

Therefore, by integrating equation (72) over the entire body and applying the above definition, the following is obtained:

$$h_o = I_x \Omega_x \vec{i} + I_y \Omega_y \vec{j} + I_z \Omega_z \vec{k} \tag{73}$$

in which case the moment of momentum components along the x, y, z axes are

$$h_x = I_x \Omega_x$$

$$h_y = I_y \Omega_y$$

$$h_z = I_z \Omega_z \tag{74}$$

It was shown previously that the moment about a body's center of gravity was equal to the time derivative of the moment of momentum.

$$\vec{M}_o = \frac{d\ h_o}{dt}$$

which in general form can be expressed as

$$\left(\frac{d\vec{h}o}{dt}\right) = \left[\frac{d\vec{h}o}{dt}\right] + \vec{\omega} \times \vec{h}_o$$

Substitute this into equation (70), Euler's moment equation is obtained,

$$\vec{M}_o = \frac{d\vec{h}o}{dt} + \vec{\Omega}_2 \times \vec{h}_o \tag{75}$$

where $\vec{\Omega}_2$ is the angular velocity of the second rotated axes system.

Taking the cross product $\vec{\Omega}_2 \times \vec{h}_o$ in a manner similar to equation (71), equation (75) becomes

$$\vec{M}_o = \left[\frac{dhx}{dt}\ \vec{i} + \frac{dhy}{dt}\vec{j} + \frac{dhz}{dt}\vec{k}\right] + \left(\Omega_{y2}h_z - \Omega_{z2}h_y\right)\vec{i}$$

$$+ \left(\Omega_{z2}h_x - \Omega_{x2}h_z\right)\vec{j} + \left(\Omega_{x2}h_y - \Omega_{y2}h_x\right)\vec{k} \tag{76}$$

and collecting terms yields

$$\vec{M}_o = \left(\frac{dhx}{dt} + \Omega_{y2}h_z - \Omega_{y2}h_y\right)\vec{i} + \left(\frac{dhy}{dt} + \Omega_{z2}h_x - \Omega_{x2}h_z\right)\vec{j}$$

$$+ \left(\frac{dhz}{dt} + \Omega_{x2}h_y - \Omega_{y2}h_x\right)\vec{k} \tag{77}$$

Now, taking the derivatives of equation (74) and remembering d(I)/dt = 0 for principal axes,

$$\frac{dhx}{dt} = I_x\dot{\Omega}_x$$

$$\frac{dhy}{dt} = I_y\dot{\Omega}_y$$

$$\frac{dhz}{dt} = I_y\dot{\Omega}_y \tag{78}$$

where $\dot{\Omega}_x$, $\dot{\Omega}_y$, $\dot{\Omega}_z$ are the derivatives of equation (62)

$$\dot{\Omega}_x = -\ddot{\phi}\cos\theta + \dot{\phi}\,\dot{\theta}\sin\theta + \dot{\omega}_{Ex_2}$$

$$\dot{\Omega}_y = \ddot{\phi} + \dot{\omega}_{Ey_2}$$

$$\dot{\Omega}_z = -\ddot{\phi}\sin\theta - \dot{\phi}\,\dot{\theta}\cos\theta + \ddot{\psi} + \dot{\omega}_{Ex_2} \tag{79}$$

and $\dot{\omega}_{Ex_2}$, $\dot{\omega}_{Ey_2}$, $\dot{\omega}_{Ez_2}$ are the derivatives of equation (61). Before taking the derivatives of equation (61), let the following be elements of equation (55) where subscripts indicate row and columns:

$$
\begin{aligned}
B_{11} &= \cos\theta \\
B_{12} &= -\sin\theta \sin\phi \\
B_{13} &= -\sin\theta \cos\phi \\
B_{21} &= 0 \\
B_{22} &= \cos\phi \\
B_{23} &= -\sin\phi \\
B_{31} &= \sin\theta \\
B_{32} &= \cos\theta \sin\phi \\
B_{33} &= \cos\theta \cos\phi
\end{aligned} \tag{80}
$$

The derivatives of equation (80) are defined here

$$
\begin{aligned}
DB_{11} &= -\dot{\theta} \sin\theta \\
DB_{12} &= -\dot{\theta} \cos\theta \sin\phi - \dot{\phi} \sin\theta \cos\phi \\
DB_{13} &= -\dot{\theta} \cos\theta \cos\phi + \dot{\phi} \sin\theta \sin\phi \\
DB_{21} &= 0 \\
DB_{22} &= -\dot{\phi} \sin\phi \\
DB_{23} &= -\dot{\phi} \cos\phi \\
DB_{31} &= \dot{\theta} \cos\theta \\
DB_{32} &= -\dot{\theta} \sin\theta \sin\phi + \dot{\phi} \cos\theta \cos\phi \\
DB_{33} &= -\dot{\theta} \sin\theta \cos\phi - \dot{\phi} \cos\theta \sin\phi
\end{aligned} \tag{81}
$$

Therefore,

$$
\begin{aligned}
\dot{\omega}_{Ex_2} &= DB_{11}\omega_{Ex} + DB_{12}\omega_{Ey} + DB_{13}\omega_{Ez} \\
\dot{\omega}_{Ey_2} &= DB_{21}\omega_{Ex} + DB_{22}\omega_{Ey} + DB_{23}\omega_{Ez} \\
\dot{\omega}_{Ez_2} &= DB_{31}\omega_{Ex} + DB_{32}\omega_{Ey} + DB_{33}\omega_{Ez}
\end{aligned} \tag{82}
$$

Substituting equations (74), (78), and (79) into equation (77) and writing $\vec{M}_o$ in component form with $I_x = I_y$,

$$M_x = I_x \left(-\ddot{\phi} \cos \theta + \dot{\phi}\, \dot{\theta} \sin \theta + \dot{\omega}_{Ex_2}\right) + \Omega_{y2} \left(I_z \Omega_z\right) - \Omega_{z2} \left(I_x \Omega_y\right)$$

$$M_y = I_x \left(\ddot{\theta} + \dot{\omega}_{Ey_2}\right) + \Omega_{z2} \left(I_x \Omega_x\right) - \Omega_{x2} \left(I_z \Omega_z\right)$$

$$M_z = I_z \left(-\ddot{\phi} \sin \theta - \dot{\phi}\, \dot{\theta} \cos \theta + \ddot{\psi} + \dot{\omega}_{Ez_2}\right) + \Omega_{x2} \left(I_x \Omega_y\right)$$

$$- \Omega_{y2} \left(I_x \Omega_x\right) \tag{83}$$

h. Summary of Equations of Motion

For convenience, the equations of motion are restated here with all terms added and in a form similar to that used in the program.

$$\frac{d^2x}{dt^2} = \frac{Fx}{m} - 2\dot{A} - \omega_{E_{yH}} C + \omega_{E_{zH}} B - Gx$$

$$\frac{d^2y}{dt^2} = \frac{Fy}{m} - 2\dot{B} - \omega_{E_{zH}} A + \omega_{E_{xH}} C - Gy$$

$$\frac{d^2z}{dt^2} = \frac{Fz}{m} - 2\dot{C} - \omega_{E_{xH}} B + \omega_{E_{yH}} A - Gz$$

$$\frac{d^2\theta}{dt^2} = \frac{My}{I_x} - \Omega_{z2}\Omega_x + \frac{\Omega_{x2} I_z \Omega_z}{I_x} - \dot{\omega}_{Ey_2}$$

$$\frac{d^2\phi}{dt^2} = \left(\frac{-Mx}{I_x} + \frac{\Omega_{y2} I_z \Omega_z}{I_x} - \Omega_{z2}\Omega_y + \frac{d\phi}{dt}\frac{d\theta}{dt} \sin \theta + \dot{\omega}_{E_{x2}}\right) \Big/ \cos \theta$$

$$\frac{d^2\psi}{dt^2} = \frac{Mz}{I_z} - \frac{\Omega_{x2} I_x \Omega_y}{I_z} + \frac{\Omega_{y2} I_x \Omega_x}{I_z} + \frac{d^2\phi}{dt^2} \sin \theta$$

$$+ \frac{d\phi}{dt}\frac{d\theta}{dt} \cos \theta - \dot{\omega}_{E_{z2}}$$

where all term are known from the initialization or from the previous time step.

Although these equations have been written for a conical shaped body with weight change due only to ablation, it only a matter of modifying the equations to include thrust and additional forces and moments associated with a finned missile.

3. INTEGRATION TECHNIQUE

To integrate a set of η simultaneous second order differential equations of the form

$$\frac{d^2xi}{dt^2} = f_i \left(t, x_1, x_2, \ldots x_\eta\right), \; i = \left(1, 2, \ldots \eta\right)$$

The Runge-Kutta method of numerical integration is recommended for this type of application and especially where a high degree of accuracy is desired. Thus, the equations of motion in the preceding subsection are shown as six second-order differential equations, which are to be solved simultaneously. This method consists of four sets of equations which involve different substitutions into the differential equations. The equations are solved, and the increments of the functions are calculated as weighted averages of the solutions to the four equations. Therefore, the integration procedure for the expression of the form

$$\frac{d^2x}{dt^2} = f\ (t, x, x')$$

is described by the following generalized equations

$$x_{n+1} = x_n + x'_\eta$$

$$x'_{n+1} = x'_n + \frac{\Delta t}{6} \left(k_0 + 2k_1 + 2k_3 + k_3\right)$$

where

$$k_0 = \Delta t\ f \left(t_n, x_n, x'_n\right)$$

$$k_1 = \Delta t\ f \left(t_n + \frac{\Delta t}{2}, x_n + \frac{\Delta t}{2} x'_n, x'_n + \frac{k_0}{2}\right)$$

$$k_2 = \Delta t \; f\left(t_n + \frac{\Delta t}{2}, \; x_n + \left(x_n' + \frac{\Delta t}{2} k\right) \; \frac{\Delta t}{2}, \; x_n' + \frac{k_1}{2}\right)$$

$$k_3 = \Delta t \; f\left(t_n + \Delta t, \; x_n + x_n'\Delta t + \frac{\Delta t}{2} k_1, \; x_n' + k_2\right)$$

In integrating a differential equation numerically, the equation is replaced by a difference equation and solved accordingly. The Runge-Kutta method has excellent properties for stability in the integration and if the integration step is taken small enough, the difference equation is usually close to the differential equation solution. However, some variables in the equations of motion may have peculiar oscillations or increase very rapidly which could cause an unstable condition or an error in the solution. An unstable condition or solution can often be made stable by using a smaller integration step. The reason for this is that different step sizes change the parameters relating to the stability of the difference solution.

The integration step size, Δt, for this program is fixed, although the user could modify the integration method to use a variable step size under error control (Ref. 14). The user has the option to break into the program at exact specified values of the independent variable, t, for the printout step.

4. AERODYNAMIC HEATING AND ABLATION

The equations of heat transfer are general in that they apply to most axially symmetric vehicles of any composite skin structure. The vehicle skin is assumed to be made of discrete layers of material whose properties may vary from layer to layer and there is no limit on the number of layers. This program is specific in that the equations have been applied to a blunt-nosed, conical vehicle.

Hypersonic vehicles may be categorized into two general types. The first consists of those vehicles which must be propelled through the atmosphere to sustain flight. The second type comprises those that have a vast store of kinetic and potential energy which will be dissipated to the surrounding air during reentry. The latter type is of primary interest and for which this program was written, although it will handle either type.

In either case, some of this energy is expended against drag forces which assume the form of skin friction and pressure drag which produce heat. The heat equivalent of the kinetic energy contained within a body is approximately

$$V_{en}^2 \; 50{,}000 \text{ (Btu/lb)}$$

where V_{en} is the reentry velocity in ft/sec. While only a fraction of this energy is actually transferred to the body as heat, this fraction is still a significant quantity and accurately illustrates the magnitude of the problem.

a. Heat Flux Equation

Experiments in high speed flow have verified that the magnitude and direction of heat flow at the surface does not depend on the difference between the wall temperature and the free-stream temperature as in low-speed flow, but rather on the difference between the wall temperature, TW, and the adiabatic wall temperature, TAW. It is apparent that the determination of the adiabatic wall temperature will be of prime importance in the calculation of heat transfer, since the transference of heat to or from the wall will depend upon whether the skin temperature is above or below TAW. The adiabatic wall temperature can conveniently be expressed in terms of a dynamic-temperature rise

$$TAW = TEMPE + RF\left(\frac{V_E^2}{2g_c C_{pa} J}\right) \tag{84}$$

where

TEMPE = boundary layer (B/L) edge temperature, °R

V_E = B/L edge velocity, ft/sec

g_c = gravitational constant, ft/sec^2

J = Joule's constant = 778

C_{pa} = specific heat of air, Btu/lb-°R

RF = recovery factor which is a measure of the fraction of the free-stream dynamic temperature rise recovered at the wall

Reference 15 shows that for practical purposes

$$RF \simeq \sqrt{PR} \tag{85a}$$

for laminar flow and

$$RF \simeq \sqrt[3]{PR} \tag{85b}$$

for turbulent flow where

PR^* = Prandtl number

$PR = C_{pa}\ \mu^*/K^*$

μ^* = viscosity of air in lb/ft-sec evaluated at reference temperature $\left(T_{REF}\right)$

K^* = thermal conductivity of air in Btu/ft-sec-°R evaluated at T_{REF}

Therefore, the unit surface convective heat rate for high-speed flow (Ref. 16) is

$$\dot{q}_c/A = \overline{h}_e \left(T_{AW} - T_W\right) \tag{86}$$

where

$\dot{q}_c/A$ = heating rate in Btu/sec-ft^2

h_e = convective heat transfer coefficient in Btu/ft^2-sec-°R

A = local wetted area in ft^2

(1) Heat Transfer Coefficient

For determining the heat transfer coefficient in laminar flow over a flat plate, an empirical method using Blasius theory was developed by Rubesin and Johnson (Ref. 17) to account for the combined effects of the local Mach number and the temperature ratio of the wall, T_W, to the boundary layer edge, TEMPE. In this method, the conventional analysis of heat transfer by convection can be used, but the reference temperature, T_{REF}, for evaluating the fluid properties is expressed as a function of the local Mach number and of the ratio T_W/TEMPE. The method has been extended to cover turbulent flow, and has proved to be both convenient and useful.

Therefore, for laminar flow the reference temperature is

$$T_{REF} = \text{TEMPE}\left[1 + 0.58\left(\frac{T_W}{\text{TEMPE}} - 1\right) + 0.032\ \text{MACHE}^2\right] \tag{87}$$

and for turbulent flow

$$T_{REF} = \text{TEMPE}\left[1 + 0.45\left(\frac{T_W}{\text{TEMPE}} - 1\right) + 0.035\ \text{MACHE}^2\right] \tag{88}$$

Equations (87) and (88) can be expressed in the form for laminar flow as

$$T_{REF} = \text{TEMPE} + 0.58 \left(T_W - \text{TEMPE}\right) + 0.19\ (\text{TAW} - \text{TEMPE}) \qquad (89)$$

and for turbulent flow as

$$T_{REF} = \text{TEMPE} + 0.45 \left(T_W - \text{TEMPE}\right) + 0.21 \left(T_{AW} - \text{TEMPE}\right) \qquad (90)$$

The heat transfer coefficient (Refs. 16, 18) is related to the flow properties through the expression

$$Nu^*(PR^*)^{1/3} = C\left(R_e\right)^a \qquad (91)$$

where

N_u^* = Nusselt number = $h_e x/K^*$

h_e = effective heat transfer coefficient

X = distance from nose, ft

K^* = thermal conductivity of air, Btu/ft-sec-°R, evaluated at T_{REF}

R_e = B/L edge Reynolds number = $\rho_e V_e X/\mu_e$

ρ_e = boundary layer edge density, lb-sec^2/ft^4

V_e = boundary layer edge velocity, ft/sec

C = 0.575 for laminar flow on cone

C = 0.0296 for turbulent flow on cone

C = 0.778 for laminar flow on blunt body

C = 0.0348 for turbulent flow on blunt body

a = 0.8 for turbulent flow

a = 0.5 for laminar flow

μ_e = B/L edge viscosity, lb-sec/ft^2

The solutions to these equations for the heat transfer coefficient is obtained by the use of the Blasius incompressible flat plate skin friction coefficients modified for compressible flow by use of Eckert's reference enthalpy. For

laminar flow

$$\frac{C_{fc}}{C_f} = \sqrt{\frac{\rho^* \mu^*}{\rho_e \mu_e}} \tag{92a}$$

and for turbulent flow

$$\frac{C_{fc}}{C_f} = \left(\frac{\mu^*}{\mu_e}\right)^{0.2} \left(\frac{\rho^*}{\rho_e}\right)^{0.8} \tag{92b}$$

Good correlation with experimental data is obtained if the gas properties are evaluated at the reference temperature and the velocity is taken as the boundary layer edge velocity. For the case of mass addition, the properties of the injected gas are used to compute the Prandtl number and Nusselt number.

It is important in the selection of a suitable material for thermal protection by the ablative process that the products of decomposition have a high specific heat. This in turn produces a high effective mean specific heat of the gas-air mixture in the boundary layer and a high Prandtl number. It is also desirable that the ablator have a low thermal conductivity. This will decrease heat conducted to the interior of the vehicle. The surface of the vehicle also receives heat by radiation from the hot gas in the shock layer in addition to that by convection. As the air density is low, its emissivity is much less than 1 percent. Therefore, the rate of radiation heat transfer is negligible compared with that of aerodynamic convection and can be ignored.

b. Unsteady Heat Conduction

A means of applying the Schmidt graphical method for solving an unsteady heat conduction problem is presented here. A thorough discussion of this method can be found in any general text (Refs. 16, 19) and will not be attempted here. This method is quite flexible in that difficult boundary conditions can be handled easily.

This method is widely used for solving unsteady heat conduction problems because it gives an iterative profile of the temperature change. Because of its simplicity, mistakes, if they occur, are easily found, and relatively untrained personnel can accomplish the work. Numerical methods are especially convenient when a high-speed digital computer is available since the steps in a numerical solution can be programmed relatively easily.

The numerical method for solving unsteady-state heat conduction differs from that used to solve steady state. In the latter case, the temperature distribution in a body can be obtained for a network of points in a solid by solving a system of residual equations. In unsteady-state systems, the initial temperature profile is known, but its variation with time must be determined. Therefore, it is necessary to resolve the temperature profile at some future time from a given distribution at an earlier time.

To illustrate the numerical method, it is necessary to transform the Fourier conduction equation (a partial differential equation that is second order in space and first order in time) for the unsteady temeprature distribution in a heat-conducting solid into a finite difference form.

$$\frac{\Delta_\tau T}{\Delta\tau} = \frac{\alpha\Delta_x^2 T}{(\Delta x)^2} \tag{93}$$

The subscripts denote the differentiation variable. Letting n denote position and t time, $\Delta_\tau T$ can be written as

$$\Delta_\tau T = T_{n,t+1} - T_{n,t}$$

and in a similar manner

$$\Delta_x T = T_{n,t+1} - T_{n,t}$$

The expression $\Delta_x^2 T$ thus becomes

$$\Delta_x^2 T = T_{n+1,t} - 2T_{n,t} + T_{n-1,t}$$

Substituting these expressions into the Fourier equation (93), gives

$$T_{n,t+1} - T_{n,t} = \frac{\alpha\Delta\tau}{(\Delta x)^2}\left(T_{n+1,t} - 2T_{n,t} + T_{n-1,t}\right) \tag{94}$$

The temperature throughout a wall or slab can now be computed for any later time if the initial distribution is known. A Schmidt plot demonstrates the temperature profile versus time in a semi-infinite slab (figure 13).

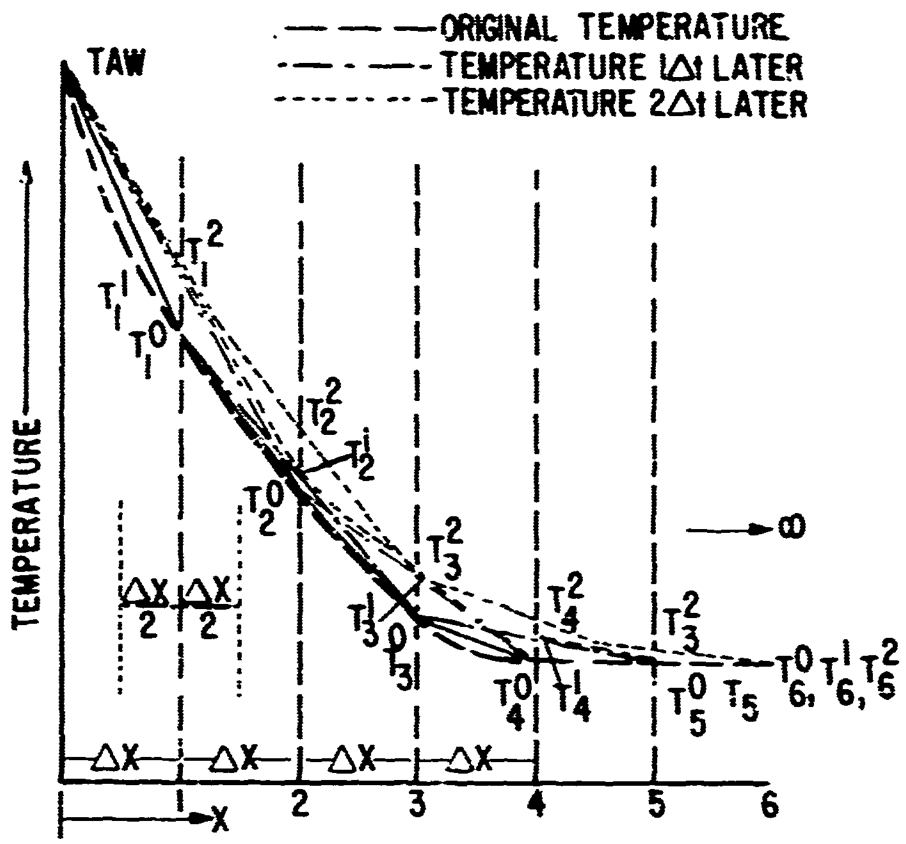


Figure 13. Schmidt Plot in an Infinitely Thick Wall

A constant wall temperature is assumed in the graphical example, but a varying wall temperature can be handled with equal ease. By letting the wall temperature vary with time, the distribution at each point within the body can be computed for each time increment.

c. Vehicle Thermal Model

To determine the time-temperature profile in the vehicle skin, the Fourier conduction equation was written as a finite difference equation and solved numerically. This method is a further adaptation of the Schmidt graphical method (Ref. 19). The wall is divided into a number of lamina with known thickness, specific heat, and thermal conductivity and with a known initial temperature distribution. Figure 14 illustrates the model with its associated nomenclature.

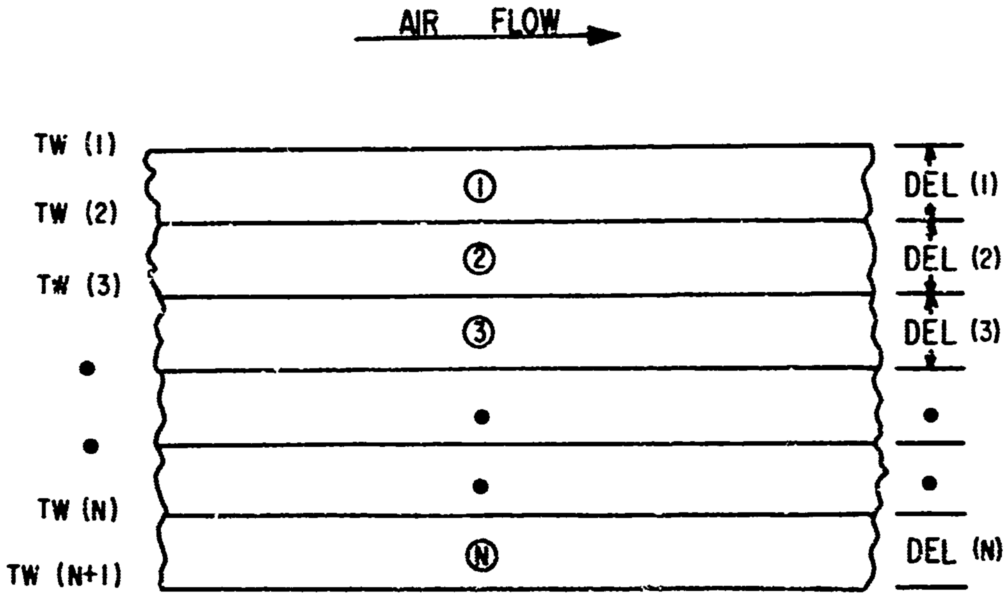


Figure 14. Model for Wall Temperature Profile and Ablation Recession Calculations

The difference equation for computing the temperature at position n at time t + 1 is

$$T_{n,t+1} = T_{n,t} + \frac{\alpha \Delta t}{(\Delta x)^2}\left(T_{n+1,t} - 2T_{n,t} + T_{n-1,t}\right) \tag{95}$$

In this form, the material properties cannot vary from layer to layer. If the properties vary from lamina to lamina, the above equation must be written in the form

$$T_{n,t+1} = T_{n,t} + \Delta t\left[\frac{\alpha_{n-1}}{\left(\Delta X_{n-1}\right)^2}\left(T_{n-1,t} - T_{n,t}\right) - \frac{\alpha_n}{\left(\Delta X_n\right)^2}\left(T_{n,t} - T_{n+1,t}\right)\right] \tag{96}$$

Where α is the thermal diffusivity and may be replaced by its defined equivalent,

$$\alpha = \frac{K}{\rho_{cp}} \tag{97}$$

where

K = thermal conductivity of material in Btu/ft-sec-°R

ρ = density of material in lbs/ft^3

cp = specific heat of material in Btu/lb-°R

This step allows one to easily recognize certain groups of terms as the heat conducted through each lamina and permits the convective heat flux to be used in solving for the wall temperature. The equation for the wall temperature is

$$T_{n-1,t+1} = T_{n-1,t} + \frac{2\Delta t}{\left(\rho_{cp}\Delta X\right)_{n-1}}\left[h_e\left(TAW - T_{n-1,t}\right)\right]$$

$$- \frac{2\Delta t\ K_{n-1}}{\left(\rho_{cp}\Delta X^2\right)_{n-1}}\left(T_{n-1,t} - T_{n,t}\right) \tag{98}$$

The backface boundary condition can be specified in several ways. If internal heating (or cooling) is present, the backface may be held constant or allowed to vary in a specified manner. A conservative assumption is that no heat flows through the last lamina. This assumption will cause somewhat more ablation and higher temperatures than would be encountered with a cooled backface or other heat sink material.

d. Ablation

Advances in hypersonic atmospheric flight have resulted in environments of extremely high temperatures. Boundary layer temperatures in excess of 10,000°F are characteristic of vehicles entering the atmosphere at hypersonic speeds.

In hypersonic flight, it becomes obvious that capacitance or mass heat-sink protection, though simple, is an inefficient means of contending with the extremely high heat fluxes associated with certain reentries or with sustained

periods of thermal flight. Consequently, other means of cooling or protecting for operating beyond heat-sink limitations must be used. One convenient means of environmental protection and for which this program was primarily written is the ablation cooling method.

The ablative process is illustrated in figure 15. The ablation process works in the following manner: (1) the material or ablator acts as a heat sink; (2) when the critical or melting temperature of the ablator is reached, a thin layer of the material at the surface will begin successively to melt, vaporize, depolymerize, or decompose chemically; and (3) as the material vaporizes, the gaseous products of decomposition enter into the boundary layer. Being relatively cool, as compared to the boundary layer air, the injected gas forms a thin, but effective film that reduces the heat transfer to the vehicle skin. It is important in the selection of a suitable material for thermal protection by the ablative process that the thermal conductivity of the material should be as low as possible so as to confine the high-temperature zone at the surface to the thinnest layer possible. Likewise, to reduce the rate of mass loss, and hence, the required weight of protective ablator, the surface temperature at which decomposition and melting begins should be as high as practicable. The products of decomposition should preferably have a high Prandtl number, since it is defined as ratio of heat storage to heat conduction of a gas. This means it is desirable to have the mean effective specific heat of the gas-air mixture in the boundary layer as large as possible.

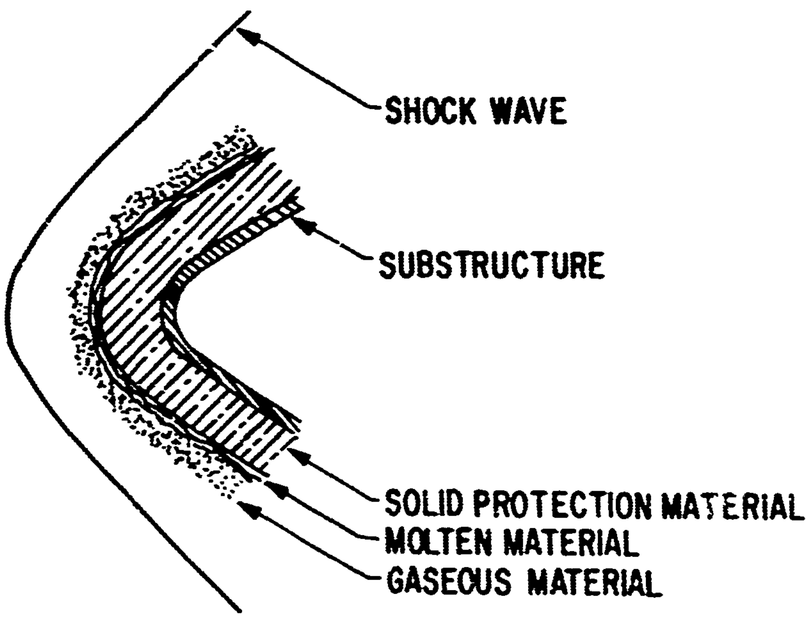


Figure 15. Ablative Process

Since the ablation process can be characterized by an exchange of material for thermal energy, the energy balance at the ablating surface, in its simplest form, is

$$\dot{q}_{net} = \dot{q}_c - \dot{q}_{cond} - \dot{q}_{rad} - \dot{q}_{block} \tag{99}$$

where $\dot{q}_c$ is heat transferred to the surface by convection, $\dot{q}_{cond}$ is the heat conducted from the surface to the substrate material, $\dot{q}_{block}$ is the heat blockage by transpiration in the boundary layer, and $\dot{q}_{rad}$ is negligible and has been ignored.

Ablation is assumed to occur when the temperature of the outermost lamina has reached the melting temperature of the material. The outer surface will recede and is assumed to take place normal to the local surface.

(1) Mass Loss and Surface Recession

Two mechanisms are involved in the loss of ablation material: (1) mass loss due to oxidation, and (2) mass loss due to sublimation. Oxidation is controlled by the diffusion of oxygen to the reacting carbon, and sublimation is controlled by local pressure and temperature. A detailed discussion on the theory of ablation and material decomposition and reaction is not the intent of this report, so only the results will be presented.

The efficiency of an ablation material is frequently defined for engineering use in terms of a quantity known as the effective heat of ablation, Q*, in Btu/lb,

$$Q^* = \frac{\dot{q}_o}{\dot{m}} \tag{100}$$

where $\dot{q}_o$ is the surface heating rate of a nonablating calorimeter at the ablative temperature, and $\dot{m}$ is the mass ablation rate. The term "effective heat of ablation" collectively expresses the ability of a material to absorb, block, and dissipate incident heat per unit mass expended. The effective heat of ablation value may also be expressed by using equations (99) and (100) as

$$Q^* = \frac{\dot{q}_{cond} + \dot{q}_{block}}{\left(1 - \dot{q}_{rad}/\dot{q}_o\right)} \tag{101}$$

or by substituting approximate equations for each gives

$$Q^* = \frac{Cp\left(T_w - T_b\right) + 0.7\left(\frac{M_{air}}{M_v}\right)^{1/4} \dot{m}_v\ (\Delta h)_o}{\left(1 - \dot{q}_{rad}/\dot{q}_o\right)} \tag{102}$$

where

Cp = heat capacity of material

T_w = ablative surface temperature

T_b = temperature of unheated material

M_{air} = molecular weight of air

M_v = molecular weight of injected gas

m_v = rate of mass injection

$(\Delta h)_o$ = enthalpy difference across boundary layer without transpiration

If the radiation, q_{rad}, is insignificant, equation (102) can be reduced to the form

$$Q^* = A + B\ (\Delta h)_o \tag{103}$$

where A is an empirical value obtained from experimental investigations of different ablators and B is dependent on whether flow is laminar or turbulent.

The surface recession rate is obtained by

$$\dot{S} = \frac{\dot{q}_c}{Q^* \rho} \tag{104}$$

where

$\dot{s}$ = recession rate, ft/sec

ρ = ablation material density, lb/ft^3

The enthalpy difference across the boundary can be calculated from the following equations:

$$(\Delta h)_o = h_r - Cp_a\ T_W \tag{105}$$

where

$$h_r = Cp_a \cdot TEMPE + RF \cdot V_E^2/\left(2g_c J\right)$$

The following are analytical expressions used in this program for determining mass loss and recession rates of three common ablators.

(a) Phenolic Refrasil (Silica)

The expression for obtaining the effective heat of ablation for Phenolic Refrasil is

$$Q^* = 4710 + B\ (\Delta h)_o \tag{106}$$

where

B = 0.58 for laminar flow

B = 0.32 for turbulent flow

(b) ATJ Graphite

The effective heat of ablation for ATJ graphite is

$$Q^* = 2000 + B\ (\Delta h)_o \tag{107}$$

where

B = 2 for either turbulent or laminar flow

(c) Carbon Phenolic

The expressions for carbon phenolic are more complicated than those used for the other materials due to reaction of carbon with atmospheric oxygen. This material has a very high melting temperature and a low thermal conductivity which gives it excellent insulation properties. Also, its products of decomposition have a high specific heat compared to that of air.

For laminar flow, the diffusion mass loss rate is given by (Refs. 20, 21)

$$\dot{M}_d = \frac{\dot{q}_c}{K1_L + K2_L\left(h_r - Cp_{BL}TW\right)} \tag{108}$$

and for turbulent flow, the expression is

$$\dot{M}_d = \frac{\dot{q}_c}{K1_T + K2_T \left(h_r - Cp_{BL} TW\right)} \tag{109}$$

where the constants K1 and K2 can be interpreted as the intercept and slope, respectively, on an effective heat of ablation versus enthalpy difference (between recovery and wall conditions) plot.

$\dot{q}_c$ = convective heat flux, Btu/ft^2-sec

h_r = recovered enthalpy, Btu/lb

Cp_{BL} = specific heat in boundary layer, Btu/lb-°R

T_W = wall temperature, -°R

$K1_L$ = 5370

$K2_L$ = 5.37

$K1_T$ = 4240

$K2_T$ = 5.77

The total mass loss rate is given by

$$\dot{M}_T = \dot{M}_d \left[1 + 2.64 \times 10^4 \,(PBL)^{-0.67} \, EXP \left(\frac{-11.05 \times 10^4}{TW}\right)\right] \tag{110}$$

where

$\dot{M}_T$ = total mass loss rate, lb/ft^2-sec

PBL = boundary layer edge pressure, lb/ft^2 (Ref. 20)

The surface recession rate is calculated by

$$\dot{S} = \dot{M}_T/\rho \tag{111}$$

where

$\dot{S}$ = recession rate, ft/sec

ρ = ablation material density, lb/ft^3

(2) Total Weight Loss Rate and Total Weight Loss

After the local instantaneous and total local recession rates have been computed, the local weight loss rate can be calculated, if needed, by determining the volume reduction of the local segment and multiplying by the material density. But the primary weight loss of interest is the total for the vehicle. To compute the total vehicle mass loss and mass loss rate, the following procedure is used. Using the local weight loss rate, the instantaneous and total recessions, and the initial radii and slant length of the particular segment of interest (see figure 16), the mass loss rate per unit area is multiplied by the appropriate surface area to give a local integrated mass loss rate. This is accomplished by the following equations:

$$\dot{WT}_{(LEN)} = PI \left(RL_{(LEN)} + RS_{(LEN)} - 2\dot{C}_{(LEN)} \right) \dot{S}\rho_c \; SOL_{(LEN)} \tag{112}$$

where

$\dot{WT}_{(LEN)}$ = instantaneous mass loss rate of segment (LEN), lb/sec

(LEN) = number of particular segment of cone

RL = larger segment radius, ft

RS = smaller segment radius, ft

$\dot{C}_{(LEN)}$ = total recession of segment, ft

$\dot{S}$ = instantaneous recession of segment, ft/sec

ρ_c = surface material density, lb/ft^3

$SOL_{(LEN)}$ = slant height of conical segment, ft

$$\dot{W} = \dot{W} + \dot{WT}_{(LEN)} \tag{113}$$

will give total vehicle mass loss rate when the operations in equation (113) are accomplished in a program "Do Loop." Summing these local rates will result in the total vehicle weight loss.

e. Stagnation Heating

To evaluate stagnation point convective heat transfer rates, this program employs Lee's theory (Ref. 22), modified by use of Eckert's reference enthalpy techniques (Ref. 19), in Lee's equation

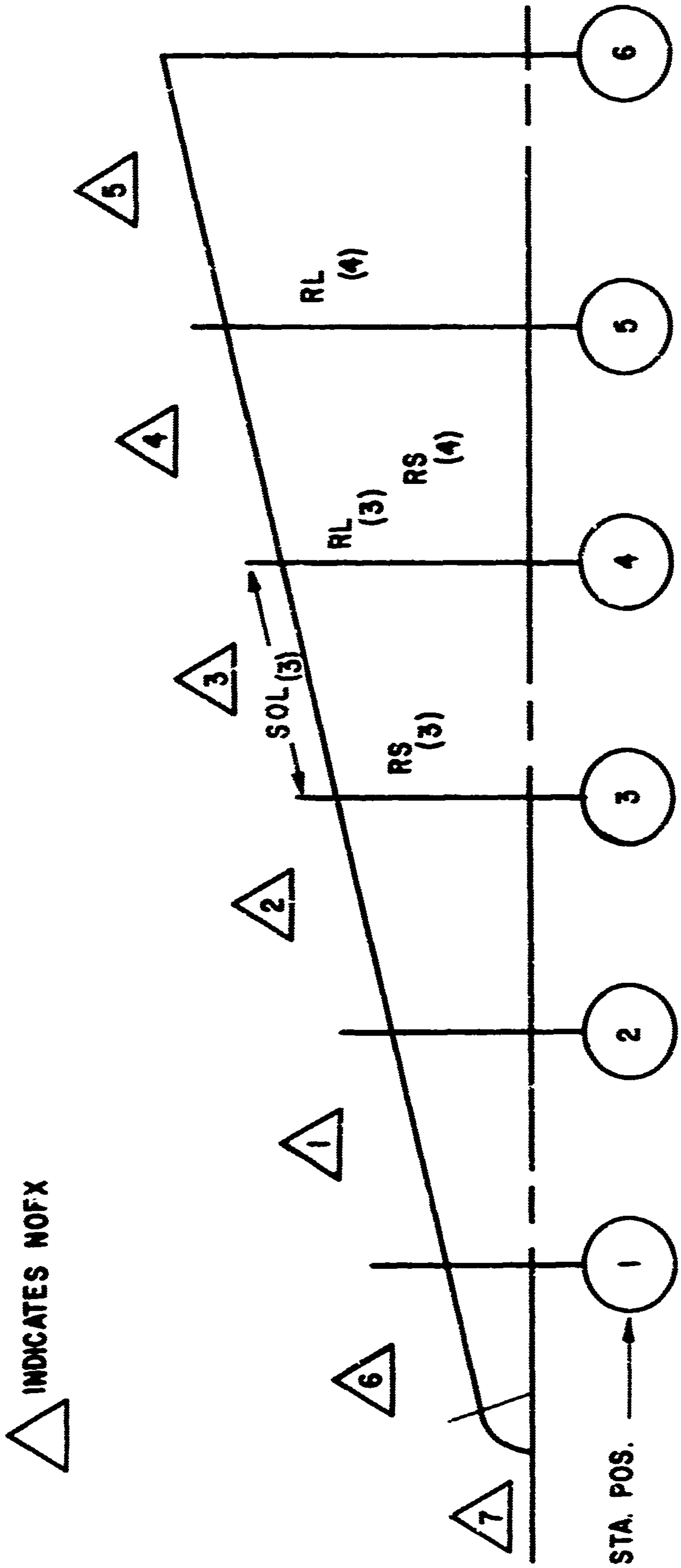


Figure 16. Vehicle Nomenclature

$$q_{c_{STAG}} = \frac{0.778}{(PR)^{2/3}} \sqrt{\rho_{WS}\mu_{WS}} \sqrt{dV/dx}\, h_{se} \cdot G\left(M_\infty, \bar{\gamma}, \gamma_\infty\right) \qquad (114)$$

where

$$G\left(M_\infty, \bar{\gamma}, \gamma_\infty\right) = \left(\frac{\bar{\gamma}-1}{\bar{\gamma}}\right)^{1/4} \left(1 + \frac{2}{\gamma_\infty - 1}\frac{1}{M_\infty^2}\right)^{1/4} \left(1 - \frac{1}{\gamma_\infty M_\infty^2}\right)^{1/4}$$

$\bar{\gamma} \simeq 1.10 - 1.20$ at high temperatures

$h_{se} = V_\infty^2/2GJ$

$\gamma_\infty = 1.4$ ratio of specific heats for air

ρ_{WS} = density evaluated at stagnation reference conditions

μ_{WS} = viscosity evaluated at stagnation reference conditions

dV/dx = velocity component gradient at the stagnation point (from Fay and Riddell)

$$\frac{dV}{dx} = \frac{1}{SNR}\left[2\left(P_S - P_\infty\right)/\rho_{WS}\right]^{0.5}$$

P_S = stagnation pressure (oblique shock)

(1) Nose Blunting

In the determination of nose blunting, it is assumed that the initial nose shape of particular interest was a sphere-cone, and after ablation the final shape was a sphere-cone. Experimental evidence has shown that the final eroded shape could be approximated by a sphere-cone having a small deviation from a sphere. The reference sphere-cone configuration after erosion is obtained by placing a spherical surface tangent to a cone parallel to the original surface but displaced by the erosion on the cone and is located axially at a position on the vehicle center line in accordance with the erosion at the stagnation point (figure 17).

The experimental evidence of nose-shape change of reentry vehicles, as previously noted, can be represented by a sphere-cone which deviates from a spherical shape by an amount less than 10 percent of the final nose radius. The final eroded nose radius can be obtained in terms of the stagnation point erosion and cone erosion as shown in the following equation:

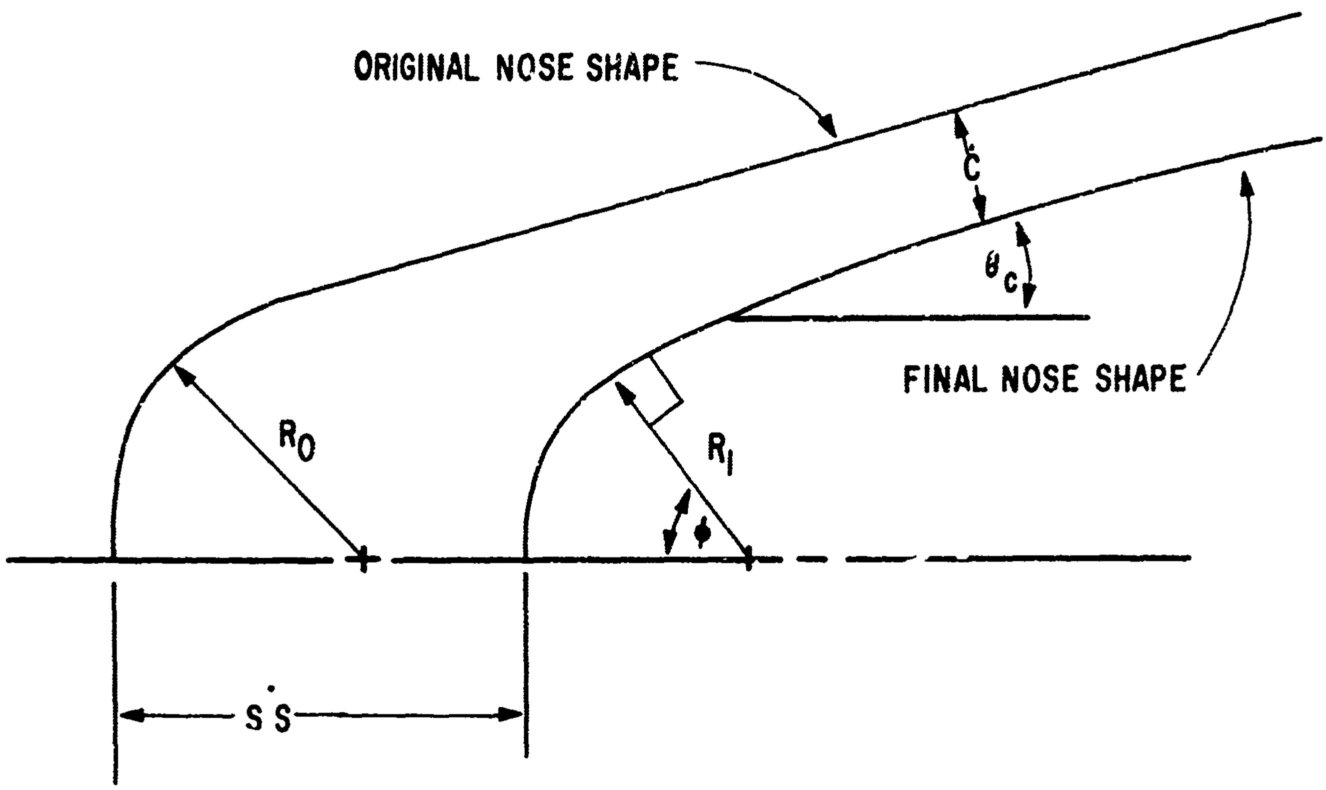


Figure 17. Vehicle Nose-Shape Change

$$R = R_o + \frac{1}{\left(1 - \sin \theta_c\right)} \left[\sin \theta_c \int_0^t \left(\frac{\dot{q}_c}{\rho Q^*}\right)_S dt - \int_0^t \left(\frac{\dot{q}_c}{\rho Q^*}\right)_C dt \right]$$

The integral represents the erosion at a given time during the flight for the locations at the stagnation point S and a point on the cone C at a location of wetted length of about five times the nose radius.

It is now possible to evaluate the final nose radius for a given application. Let

$$\dot{S}_S = \int_0^t \left(\frac{\dot{q}_c}{\rho Q^*}\right)_S dt \tag{115}$$

and

$$\dot{C} = \int_0^t \left(\frac{\dot{q}_c}{\rho Q^*}\right)_C dt \tag{116}$$

therefore

$$R = R_o + \frac{1}{\left(1 - \sin \theta_c\right)} \left[\sin \theta_c \, \dot{S}_S - \dot{C}\right] \tag{117}$$

where

R_o = original nose radius, ft

R = instantaneous nose radius, ft

θ_c = cone half-angle

$\dot{S}_S$ = stagnation point recession rate, ft/sec

$\dot{C}$ = recession rate at location, C, ft/sec (see figure 17)

f. Boundary Layer Transition

The problem of transition from laminar to turbulent boundary layer flow has always been a troublesome one for the aeronautical engineer. The standard approach usually has been to design conservatively, that is, for turbulent flow. In general, the transition Reynolds number has been found to primarily depend upon the local Mach number, which has been observed in the analysis of boundary layer transition on a series of flight vehicles. Transition on blunt spherical nose vehicles with low boundary layer edge Mach numbers appears to occur at Reynolds number of 1.5×10^6, while on sharp bodies where the edge of the boundary layer edge Mach numbers approach 10 Reynolds numbers as high as 2.0×10^7 have been observed prior to transition. Thus, for untested vehicle configurations, it is necessary to investigate the relationship of the Mach number and the Reynolds number in both the high and low Mach number regions. This relationship between Mach number and Reynolds number stands to reason if their definitions are understood. The parameter Mach number describes the influence of compressibility on heat transfer and flow phenomena and is defined

as the ratio of the gas or flight velocity to the local or ambient speed of sound. The Reynolds number, which describes the nature of flow, is a dimensionless measure of the ratio of inertial to viscous forces.

It should be noted that flight data on sharp bodies indicate that, generally, transition does not occur instantaneously over the entire vehicle so that it may travel several thousand feet between the onset of transition and the establishment of a fully turbulent boundary layer. See references 23 and 24.

The approach used in this program is to apply the sharp and blunt body transition Reynolds numbers simultaneously. Therefore, the sharp body criterion is described by the expression

$$Re_{TRAN} = 6.6 \times 10^7$$

and the blunt body criterion is applied when either of the following two Reynolds numbers are reached with conditions stated

$Re_{TRAN} = 1.5 \times 10^6$ on the spherical nose

$Re_{TRAN} = 5.0 \times 10^6$ on the conical portion aft of the spherical nose for a wetted length of five times the nose radius.

The above criteria has been found to correlate with experimental data.

5. AERODYNAMICS

The one item that plays the most significant role in determining the performance of a high velocity or hypersonic reentry vehicle is aerodynamic drag. Experimental results have been correlated with theoretical studies of the nonsteady effects on a reentry vehicle or missile during its trajectory. These results indicate that the aerodynamic forces can be determined accurately by assuming quasi-steady flow conditions; that is, the flow field at any instant of time is the same as that associated with steady motion at the same velocity. Furthermore, it has been demonstrated that the boundary layer behaves in a quasi-steady manner. Therefore, assuming that the validity of these results carry over for an ablating blunt cone, the instantaneous drag coefficients can be obtained from equivalent steady-state conditions.

This program asumes that the drag consists of three components: cone pressure or forebody drag, base pressure drag, and skin friction or viscous drag. It is convenient to consider these quantities as distinct quantities which can be added together to obtain the total vehicle drag. Though all these quantities are distinct, some are dependent upon the boundary layer condition. For example, the condition of the boundary layer, laminar or turbulent, which influences the viscous drag can also influence the base drag.

a. Cone Pressure Drag

The forebody pressure drag for a slender body at zero angle-of-attack or at incidence can be calculated on the basis of the modified slender-body theory.

The forebody pressure drag is defined by the relation

$$D_p = - \iint_{S_m} P \cos\left(n, V_\infty\right) d\, S_m$$

where $\cos\left(n, V_\infty\right)$ is the cosine of the angle between V_∞ and the outward normal to the vehicle surface. The area S_m comprises the total area of the vehicle except base area.

For a sharp cone at $\alpha = 0$, the pressure P_c is constant over the entire body, and the forebody drag is then only a function of the pressure ratio P_c/P_∞ across the conical shock. Solutions for this pressure ratio as a function of Mach number and cone angle, θ_c, have been tabulated by Kopal (Ref. 25) for the ratio of specific heats of $\gamma = 1.405$. These r sults have been employed directly in the drag equation in order to obtain the forebody drag on a sharp cone. The analysis produced the equation

$$C_{Dp} = 4 \sin^2 \theta_c \left[\frac{2.5 + 8 M_\infty \sin \theta_c}{1 + 16 M_\infty \sin \theta_c}\right] \tag{118}$$

which is similar to the form of the Newtonian drag equation for a sharp cone. The last term represents the variation from the Newtonian theory due to Mach number effects.

Nose blunting of a cone will increase the pressure drag. Local overpressures are induced near a blunt nose by the strong nose-shock curvature. The results of sharp and blunt body solutions have been correlated as a function of M_∞, θ_c, and R_N/R_B. However, for bluntness ratios, R_N/R_B less than 0.05, the values for the drag due to the overpressures are low compared to C_{Dp}.

This program do. ̦ account for the drag due to the nose being blunt within the limits expressed above. The sharp cone drag is modified by assuming the nose drag to be that of a sphere minus that of the cone replaced by the sphere. Because both of these terms are referenced to the projected area of the sphere, the area or bluntness ratio, R_N/R_B, term is needed as a correctness factor. Therfore, the pressure coefficient for a blunt cone is (Ref. 26)

$$C_{Dp_{cone}} = C_{Dp} + \left[0.58 - C_{Dp}\right]\left(\frac{R_N}{R_B}\right)^2 \tag{119}$$

where 0.58 is drag coefficient for a sphere obtained from reference 27

C_{Dp} is from equation (118)

R_N/R_B is the bluntness ratio of nose radius to cone base radius

b. Skin-Friction Drag

The skin-friction or viscous drag is defined as

$$D_V = \iint_{S_m} \tau \cos\left(t, V_\infty\right) d\, S_m$$

where τ is the local skin friction per unit area due to viscosity, and $\cos\left(t, V_\infty\right)$ is the cosine of the angle between V_∞ and the tangent to the vehicle surface in the τ direction as shown in figure 18.

The skin-friction drag coefficient can be defined as

$$C_{Df} = \frac{2\pi}{A_B} \int_0^L C_{f_\infty} \cos \phi \; r\, dx \tag{120}$$

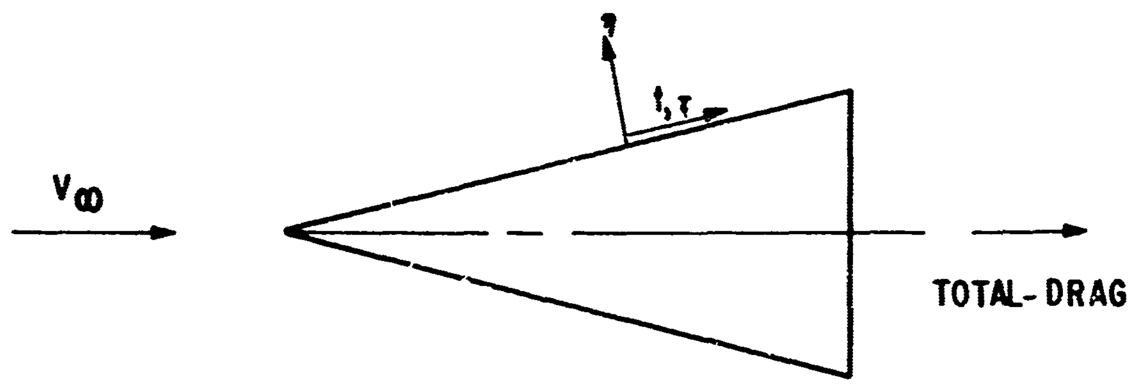


Figure 18. Aerodynamic Body Subject to Normal and Tangential Forces

where C_{f_∞} is the local skin-friction coefficient defined as

$$C_{f_\infty} = \frac{\tau}{1/2\ \rho\ V_o^2} \tag{121}$$

(1) Local Skin-Friction Coefficient

(a) Laminar Flow, $\alpha = 0$

The local skin-friction coefficient is calculated using the Blasius flat plate in compressible solution. The flat plate solution was modified for conical flow by the Mangler transformation (Ref. 28) and for compressibility by Eckert's reference enthalpy method (Ref. 29).

The modified Blasius equation is

$$C_f = \frac{0.664}{\sqrt{Re_x}} \quad \sqrt{3} \quad \sqrt{\frac{\rho^*\mu^*}{\rho_e\mu_e}\left(\frac{\rho_e V_e^2}{\rho_\infty V_\infty^2}\right)} \tag{122}$$

where

$Re_x = \frac{\rho_e V_e x}{\mu_e}$ boundary layer edge Reynolds number

x = distance along sharp cone surface

ρ_e = density of air

μ_e = viscosity of air

V_e = velocity

The superscript * and subscripts e and ∞ signify the property is evaluated at the reference enthalpy or conditions at the edge of boundary layer or free stream, respectively.

Equation (121) can be simplified to

$$C_{f_\infty} = \frac{1.15}{\sqrt{x}} \frac{V_e^{1.5}\left(\rho^*\mu^*\right)^{0.5}}{\rho_\infty V_\infty^2} \tag{123}$$

Letting

$$R_{\infty_x} = \frac{\rho_\infty V_\infty x}{\mu_\infty}$$

and rearranging equation (123),

$$C_{f_\infty} = \frac{1.15}{\sqrt{R_{\infty_x}}}\left(\frac{V_e}{V}\right)^{1.5} \sqrt{\frac{\rho^*\mu^*}{\rho_\infty\mu_\infty}} \tag{124}$$

From references 30 and 31, the quantity

$$\sqrt{\frac{\rho^*\mu^*}{\rho_\infty\mu_\infty}}$$

can be replaced by

$$\sqrt{\frac{\rho^*\mu^*}{\rho_\infty\mu_\infty}} = \left(\frac{p_c}{p_\infty}\right)^{0.5} \left(\frac{h^*}{h_\infty}\right)^{-0.185}$$

where

$$\frac{h^*}{h_\infty} = \frac{h^*}{h_e}\frac{T_e}{T_\infty}$$

It is assumed that cone pressure p_c is equal to boundary layer edge pressure, p_e, the free-stream specific heat is equal to the boundary layer edge specific heat, the specific heat ratio is $\gamma = 1.405$, and the recovery factor, R_F, is equal to 0.8426. Therefore, equation (123) for the local skin-friction coefficient can be written as

$$C_{f_\infty} = \frac{1.15}{\sqrt{R_{\infty_x}}} \left(\frac{V_e}{V_\infty}\right)^{1.5} \left(\frac{p_e}{p_\infty}\right)^{0.5} \left(\frac{T_e}{T_\infty}\right)^{-0.185} \left(\frac{h^*}{h_e}\right)^{-0.185} \tag{125}$$

where

$$\frac{h^*}{h_e} = 0.5 + 0.5 \ \frac{TW}{T_\infty}\left(\frac{T_e}{T_\infty}\right)^{-1} + 0.0374\ M_e^2 \tag{126}$$

The ratios,

$$\left(\frac{V_e}{V_\infty}\right)$$

$$\left(\frac{p_e}{p_\infty}\right)$$

$$\left(\frac{T_e}{T_\infty}\right)$$

are obtained from conical flow results given by Bertram (Refs. 31 and 32) which have been correlated as a function of the hypersonic similarity parameter, $M_\infty \sin \theta_c = K_c$. A curve-fit of these results produced the following relations:

$$\frac{V_e}{V_\infty} = \left[1 - \frac{1.4}{M_\infty^2}\left(K_c\right)^{1.9}\right]^{0.5} \tag{127}$$

$$\frac{p_e}{p_\infty} = 1 + 2.8\ K_c^2 \left[\frac{2.5 + 8\ K_c}{1 + 16\ K_c}\right] \tag{128}$$

$$\frac{T_e}{T_\infty} = 1 + 0.0966\ K_c + 0.2267\left(K_c\right)^2 \tag{129}$$

The local Mach number can be computed from

$$\frac{M_e}{M_\infty} = \frac{V_e}{\sqrt{\gamma_e R_e T_e}} \cdot \frac{\sqrt{\gamma_\infty R_\infty T_\infty}}{V_\infty}$$

From previous assumptions and reducing

$$\frac{M_e}{M_\infty} = \frac{V_e}{V_\infty}\left(\frac{T_e}{T_\infty}\right)^{-0.5} \tag{130}$$

The local laminar skin-friction is now defined in terms of free-stream conditions, wall temperature, and cone angle.

(b) Turbulent Flow, $\alpha = 0$

Using the Blasius flat plate incompressible solution modified in a similar manner for conical flow and compressibility, the Blasius equation for the local skin friction coefficient in turbulent flow is

$$C_{f_\infty} = \frac{0.0698}{R_{ex}^{0.2}}\left(\frac{\rho^*}{\rho_e}\right)^{0.8}\left(\frac{\mu^*}{\mu_e}\right)^{0.2}\frac{\rho_e V_e^2}{\rho_\infty V_\infty^2} \tag{131}$$

By substituting in a manner similar to laminar flow, and using the same ratios and rearranging, the following expression for the turbulent skin-friction coefficient in terms of free-stream conditions, wall temperature, and cone angle is given by

$$C_{f_\infty} = \frac{0.0698}{\left(R_{\infty x}\right)^{0.2}}\left(\frac{V_e}{V_\infty}\right)^{1.8}\left(\frac{P_e}{P_\infty}\right)^{0.8}\left(\frac{h^*}{h_e}\right)^{-0.58}\left(\frac{T_e}{T_\infty}\right)^{-0.58} \tag{132}$$

where

$$\left(\frac{h^*}{h_e}\right) = 0.5 + 0.5\left(\frac{T_w}{T_\infty}\right)\left(\frac{T_e}{T_\infty}\right)^{-1} + 0.0388\ M_e^2$$

for $R_F = 0.877$.

(2) Average Skin-Friction Coefficient

To obtain the average skin-friction coefficient for both laminar and turbulent flow, the local value must be integrated over the cone surface. Therefore, substituting πR_B^2 for A_B in equation (120) and rearranging

$$C_{Df} = \frac{2\pi}{\pi R_B^2} \int_0^L C_{f_\infty} \cos\theta \,(r)\, dx \tag{133}$$

but

$$C_{f_\infty} = \left(C_{f_\infty}\right)_{x=L} \left(\frac{L}{x}\right)^{0.5}$$

and

$$R_B^2 = L^2 \sin^2 \theta_c$$

$$r = x \sin \theta_c$$

Substituting these relations into equation (133), then

$$C_{Df} = \frac{2}{L^2 \sin^2 \theta_c} \left(C_{f_\infty}\right)_{x=L} (L)^{0.5} \cos\theta_c \sin\theta_c \int_0^L (x)^{-0.5}\, dx \tag{134}$$

Now, combining equation (134) with equations (125) and (133), the average skin-friction coefficients for laminar and turbulent flow are, respectively,

$$C_{D_{F_L}} = \frac{1.533}{\sqrt{R_{\infty_L}}} \left(\frac{V_e}{V_\infty}\right)^{1.5} \left(\frac{P_e}{P_\infty}\right)^{0.5} \left(\frac{T_\infty}{T_e}\right)^{0.185} \left(\frac{h_e}{h^*}\right)^{0.18\text{[illegible]}} \left(\cot \theta_c\right)$$

and

$$C_{D_{F_T}} = \frac{0.0776}{\left(R_{\infty_L}\right)^{0.2}} \left(\frac{V_e}{V_\infty}\right)^{1.\text{[illegible]}} \left(\frac{P_e}{P_\infty}\right)^{0.\text{[illegible]}} \left(\frac{T_\infty}{T_e}\right)^{\text{[illegible]}} \left(\frac{h_e}{h^*}\right)^{\text{[illegible]}} \left(\cot \theta_c\right) \tag{135}$$

The wall temperature used in the enthalpy ratio equation is taken as an average temperature over the entire vehicle surface.

c. Base Drag

The base pressure drag is determined by the mechanics of the wake, for which there is as yet no complete theory. Values of the base pressure coefficient C_{PB} must be obtained experimentally. Because of this, analytical methods of treating base drag are usually replaced by a correlation of experimental results. As the vehicle velocity increases, the base pressure, and therefore, the base-drag coefficient are affected similarly to other pressures. Once the speed is well into the supersonic region, most base pressures for a cone approach about 70 percent of a vacuum. Hoerner (Ref. 33) has correlated a wide variety of data for conical flow with the following result:

$$C_{PB} = 1.43/M_\infty^2 \tag{136}$$

for a vacuum. Reducing this by 70 percent

$$C_{PB} = 1.001/M_\infty^2 \tag{137}$$

for $M \geq 2$.

d. Stability Derivatives

The stability derivatives used in this program are for a sharp cone and are easily derived from references 34 and 35. These derivatives consisted of the damping coefficient per radian of pitch angle of attack, CMQ, and the rate of change of the normal force coeficient per degree of pitch angle of attack, CN_α. These values are for the following cone conditions:

$$4.0° < \theta_c < 10°$$

and

$$0 < R_N/R_B < 0.3$$

The rate of change of pitching moment coefficient, CMA, can be computed as

$$CMA = -(SM)(CNA)/DIA \tag{138}$$

where

SM = static margin in feet

DIA = reference diameter in feet

Because of the symmetry of the conical vehicle used in this program, the values produced by yaw angle of attack and yaw angular velocities are equal in magnitude to pitch (data). Therefore,

$$CNR = CMQ \tag{139}$$

$$CNB = -CMA \tag{140}$$

$$CYB = -CNA \tag{141}$$

The derivatives are used to compute the aerodynamic forces and moments needed to restore the vehicle to zero angle of attack in pitch and yaw.

SECTION III

SUBROUTINES

1. ATMOSPHERIC PROPERTIES

The following list of subroutines are incorporated in STRAB-6 to compute the necessary atmospheric properties. This atmosphere uses the equations derived for the 1962 U.S. Standard atmosphere.

a. Subroutine RHOF

This subroutine computes the atmospheric density as a function of geometric altitude from the main program. The geometric altitude is converted to geopotential altitude in the subroutine and the density is computed accordingly. The units of density, Rho, are lbs-sec^2/ft^4.

b. Subroutine VSD

This subroutine calculates the velocity of sound, VS, in feet/sec as a function of geometric altitude.

c. Subroutine TEMPA

The ambient temperature, TEMP, is calculated in this subroutine as a function of geometric altitude. The units are degrees R.

d. Subroutine VISCO

This subroutine computes the viscosity of air as a function of geometric altitude. The units are lb-sec/ft^2.

e. Subroutine PRESS

The ambient pressure, PE, is calculated in this subroutine as a function of geometric altitude. The units are lb/ft^2.

2. HOT AIR PROPERTIES

a. Subroutine VISCOT

This subroutine calculates the viscosity of air as a function of temperature. It is used primarily for the hot air in the nonablating boundary layer. The units are lb/sec-ft.

b. Subroutine TCAT

The thermal conductivity, TCA, of hot air is calculated in this subroutine as a function of temperature. The units of TCA are Btu/ft-sec-°R.

3. ABLATOR THERMAL PROPERTIES

The following subroutines are used to compute the thermal properties of carbon phenolic, phenolic silica (Refrasil), and ATJ graphite. The properties computed are the thermal conductivity and the specific heat. The carbon phenolic and phenolic silica ablator have both virgin and char properties as well as densities. From all available data for ATJ graphite, it appears that no distinction is made between virgin or char conditions. The subroutines that compute the thermal properties for carbon phenolic and phenolic silica have the same names to minimize card changes in the main program.

a. Subroutine VTCPC

This subroutine computes the virgin thermal conductivity for carbon phenolic or for phenolic refrasil as a function of wall temperature. The units are Btu/ft-sec-°R.

b. Subroutine VCPPC

The virgin specific heat for carbon phenolic or phenolic silica is calculated by this subroutine as a function of wall temperature. The units are Btu/lb-°R.

c. Subroutine CTCPC

The char thermal conductivity for carbon phenolic or phenolic silica is computed by this subroutine as a function of wall temperature. The units are in Btu/ft-sec-°R.

d. Subroutine CCPP

This subroutine computes the char specific heat of carbon phenolic or phenolic silica as a function of wall temperature. The units are Btu/lb-°R.

4. ABLATION GAS PROPERTIES

Subroutines GCPB and GASTC compute the thermal properties of the ablative gas-air mixture in the boundary layer. These subroutines are used with the carbon phenolic ablator only. They compute the gas specific heat and gas thermal conductivity. The values associated with phenolic refrasil and ATJ graphite are inputted as single values.

5. STABILITY DERIVATIVES SUBROUTINES

These subroutines are incorporated into STRAB-6 for computation of the necessary aerodynamics discussed in section II-5. The equations are general for the following cone parameters:

$$4.0° < \theta_c < 10.0°$$

$$0 < R_N/R_B < 0.3$$

$$3.0 < M_\infty < 30$$

a. Subroutine CDSF

This subroutine calculates the aerodynamic drag coefficients CP, CAN, CPB, and CDF as a function of M_∞ or Reynolds number. CDSF is called for in the main program.

(1) Subroutine CDFM

This subroutine computes the skin-friction drag, CDF, and is called into the program through subroutine CDSF. The boundary layer edge properties are calculated in this subroutine.

b. Subroutine ACMQ

The damping coefficient, CMQ, is calculated in this subroutine as a function of free-stream Mach number. CMQ is per radian.

c. Subroutine ACNA

This subroutine computes the normal force coefficient, CNA, as a function of free-stream Mach number. CNA is per radian.

6. SUBROUTINE INITIAL (Ref. 36)

This subroutine is incorporated into STRAB-6 to provide the necessary vehicle geometry calculations and changes in units. By reading in vehicle axial stations of interest, the subroutine will compute the transition Reynolds number, slant height (SOL), smaller radius (RS), and larger radius (RL) for each conical segment. It will also compute the appropriate cone base radius and total slant height. See figure 16 for further clarification.

7. SUBROUTINE ATTK AND SSLP

These subroutines are used to compute the complete range of angles of attack, ALP, and sideslip, BFT. These angles are computed as a function of the components of the relative velocity.

8. SUBROUTINE DLON

This subroutine computes the longitude of the vehicle with respect to the earth reference system. See section II-2c for derivation.

SECTION IV

PROGRAM OPERATION

1. INPUT DATA REQUIREMENT

All input data that is subject to change either due to vehicle or trajectory requirements are read into STRAB-6 from the data statement. The word data is punched first, then the FORTRAN symbol, and then the numerical values. The symbols and numerical values are punched in Columns 7 through 72, inclusive, with up to nine continuation cards if needed. Columns 73 to 80, inclusive, can be used for comments or identification. The numerical values can be punched in any format except "I." Care should be taken to keep the symbol and its corresponding value in the same sequence. For example:

```
DATA V. AZN, NOFX, NAL, GAMMA/22414., 123.003, 8, 4, -39.92/
```

Also,

```
DATA WE, REQ, ET/0.729E-04, 20,927491E+06, 8.18133302E-02/
```

Another method of data card is

```
DATA (POS (I), I = 1, 6)/3.338, 15.189, 27.040, 38.851, 50.742, 65.556/
```

Another flexibility of the input routine, aside from the fact that the data can be introduced in any order of the symbols (with their associated values), is the feature that permits inputting the same symbol (and an associated value) again, thus superseding the previous value. This feature is convenient when basically constant vehicle configurations and initial conditions are maintained in many runs with only a few quantities changing. The "Standard" input data cards may be kept intact, and only the varying quantities may be punched on a card after the data cards which may be removed later.

For the heating portion of the program, there are several "Do Loops" that initialize temperatures, ablator lamina thickness, control indicators, and thermal properties of the adhesive bond and backface aluminum shell. Also, there are various equations to obtain initial trajectory conditions as well as initial dummy program starters.

a. Multi-Case Run

This program readily lends itself for a multi-case run with a minimal change. If the need arises for a parametric study of various vehicle geometry and trajectory missions, the following changes can be made to some of the data inputs and check for completion of the multi-case run.

```
Read 1500, NCASE, (POS(J), J=1, 8) 1500 FORMAT (I2, 7A10, A8)

Print 1501, NCASE, (POS(J), J-1, 8) 1501 FORMAT (1H1, 30X, 7A10, A8)
```

These read and print statements allow the identifier to be read into the program and case heading to be printed out before that particular case data output. The 1500 format allows the case number to be punched in the first two columns. When a zero is in these columns, the program will go to end with this check statement.

```
If (NCASE.NE.0) go to 1700
END
```

where statement 1700 would be the return at the beginning of the program to start another case.

To update the vehicle configuration and trajectory parameters, the following data input is used

```
Read 1300, (POS(I), I=1,NOFX)

Read 1300, THETC, GAMMA, BI

Read 1300, V, AXN, GLAT, DLON

Read 1300, ALGTH, SNR 1300 Format (8F10.2)
```

All other data input cards would remain the same. See appendix II for multi-case listing and setup.

2. OUTPUT DATA REQUIREMENTS

The output quantities of the program and sample case are shown in appendixes I and III.

Before the printout of any results, a listing of the program and input data cards are printed. This record of the actual program listing and data input will assist in the identification of a run as well as an aid in troubleshooting in the event of arithmetic errors.

The first block of data printout of the matrix of temperatures, lamina thickness, etc., are obtained from the initialization "Do Loops" for heating portion of the program. This printout is done only once.

The second block of data is the trajectory output, aerodynamic coefficients, and boundary layer edge values. The next block of output is the wall and skin-profile temperatures, total recession, integrated weight loss rate, and total weight loss.

Printout is regulated by a time indicator. Data can be printed out at any time step desired. If a printout of data is wanted every 0.1 second, set BT = .1. The following method will then allow printout at that time step.

```
BTL = BT - H/6.

BTH = BT + H/6.

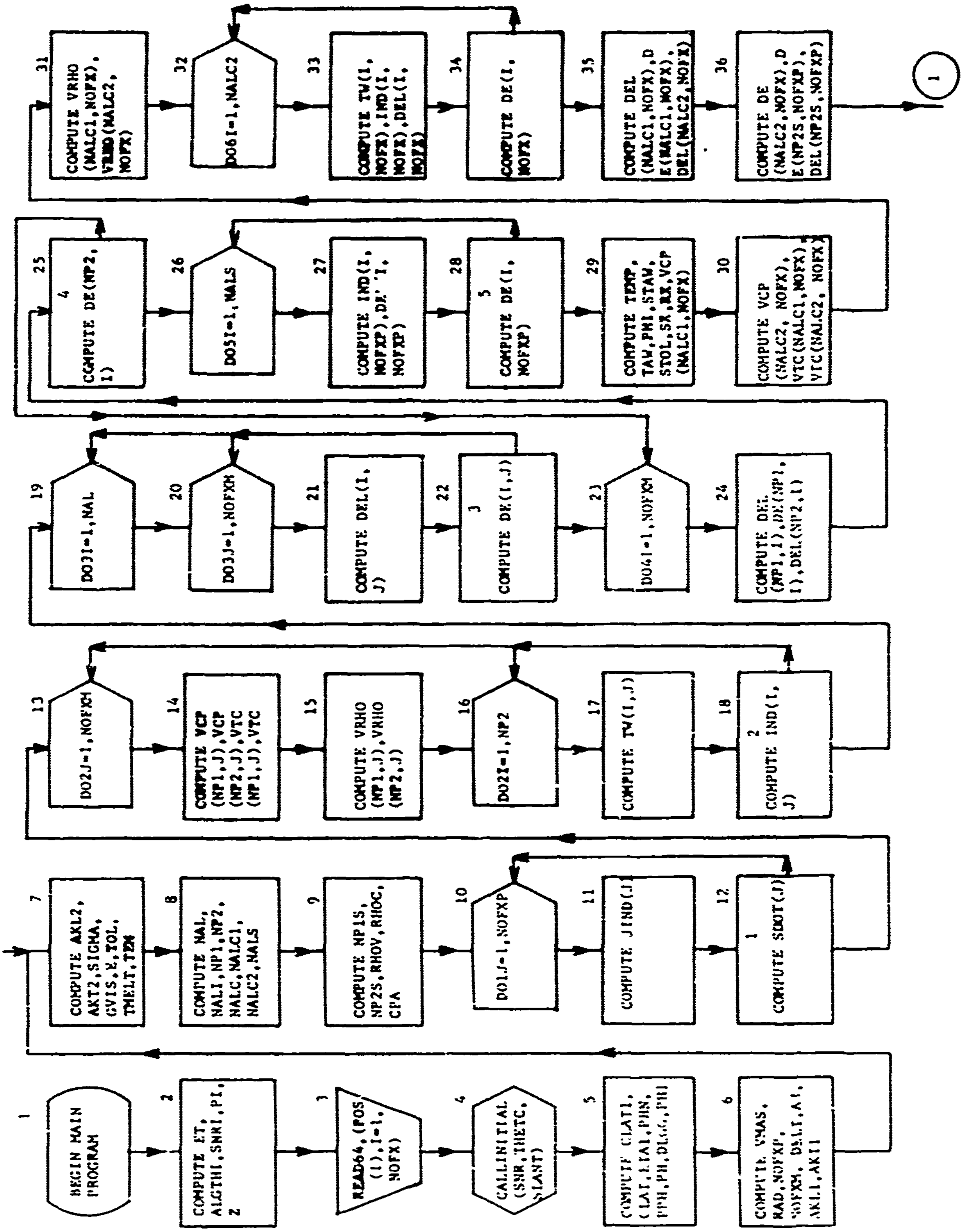
If (T  .GT.BTL . AND. T. LT. BTH) go to (statement number)

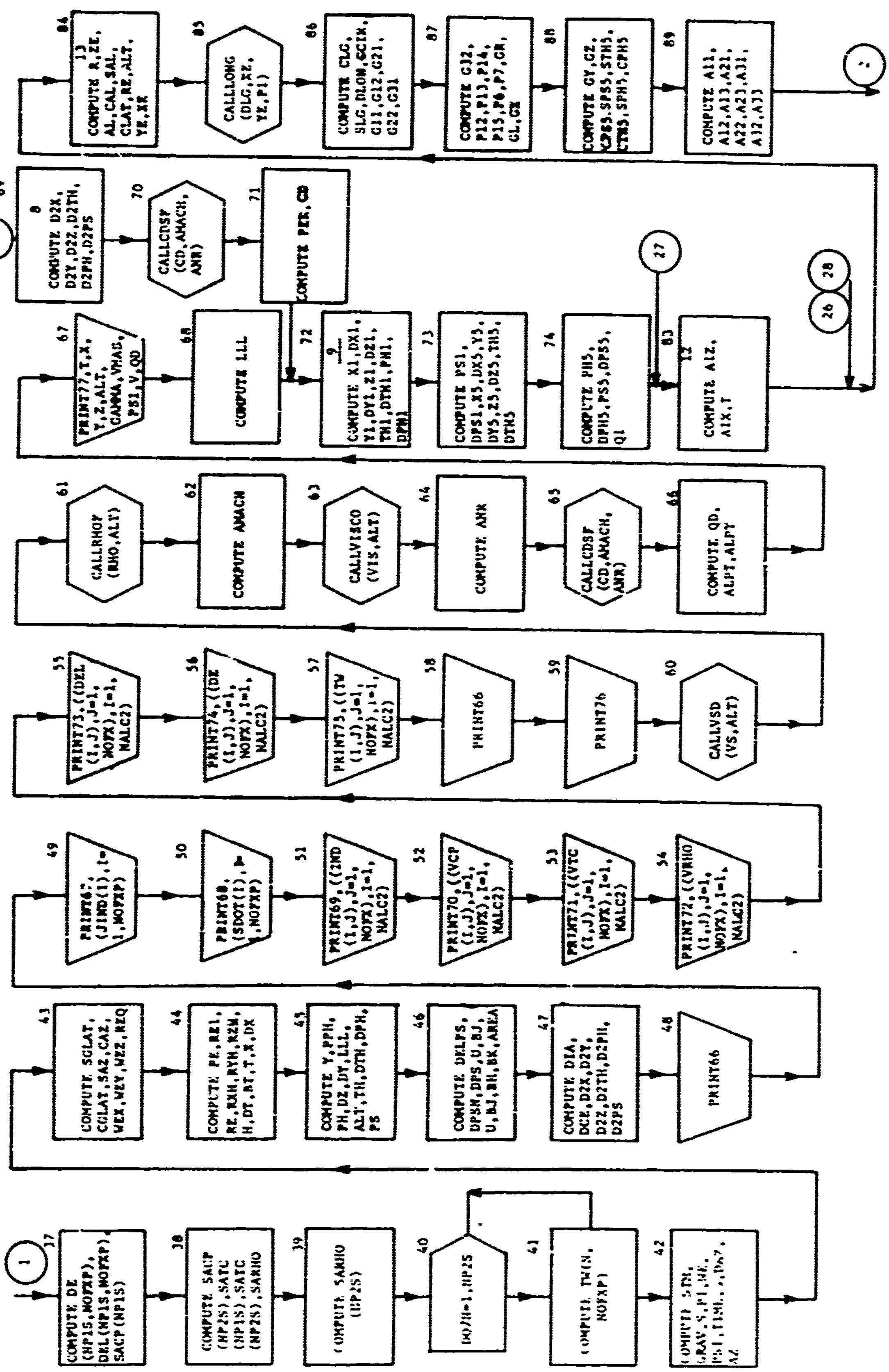
BT = BT + .1
```

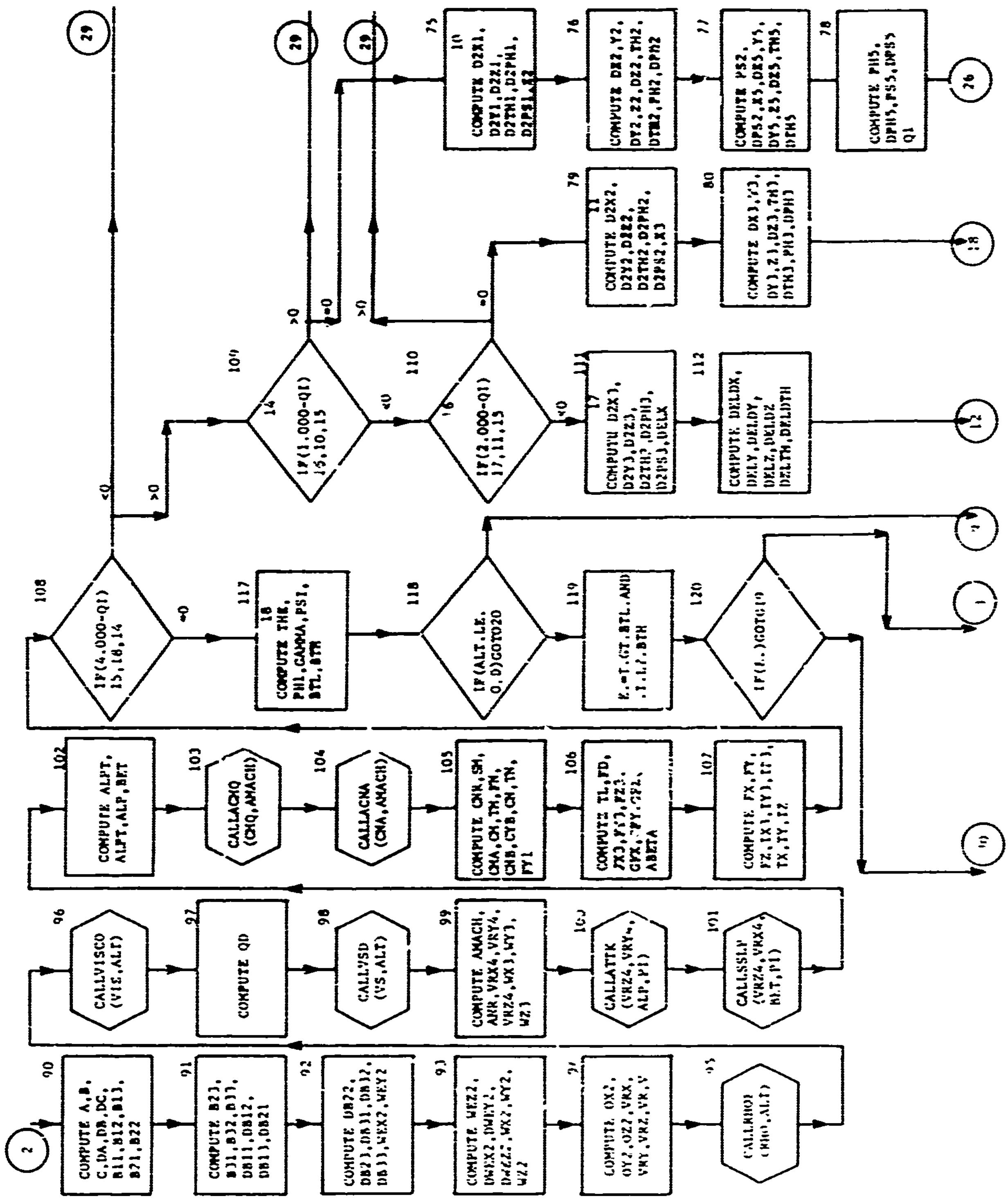
where H is the Runge-Kutta integration time step. This method will allow data printout and also go into the heating portion of the program.

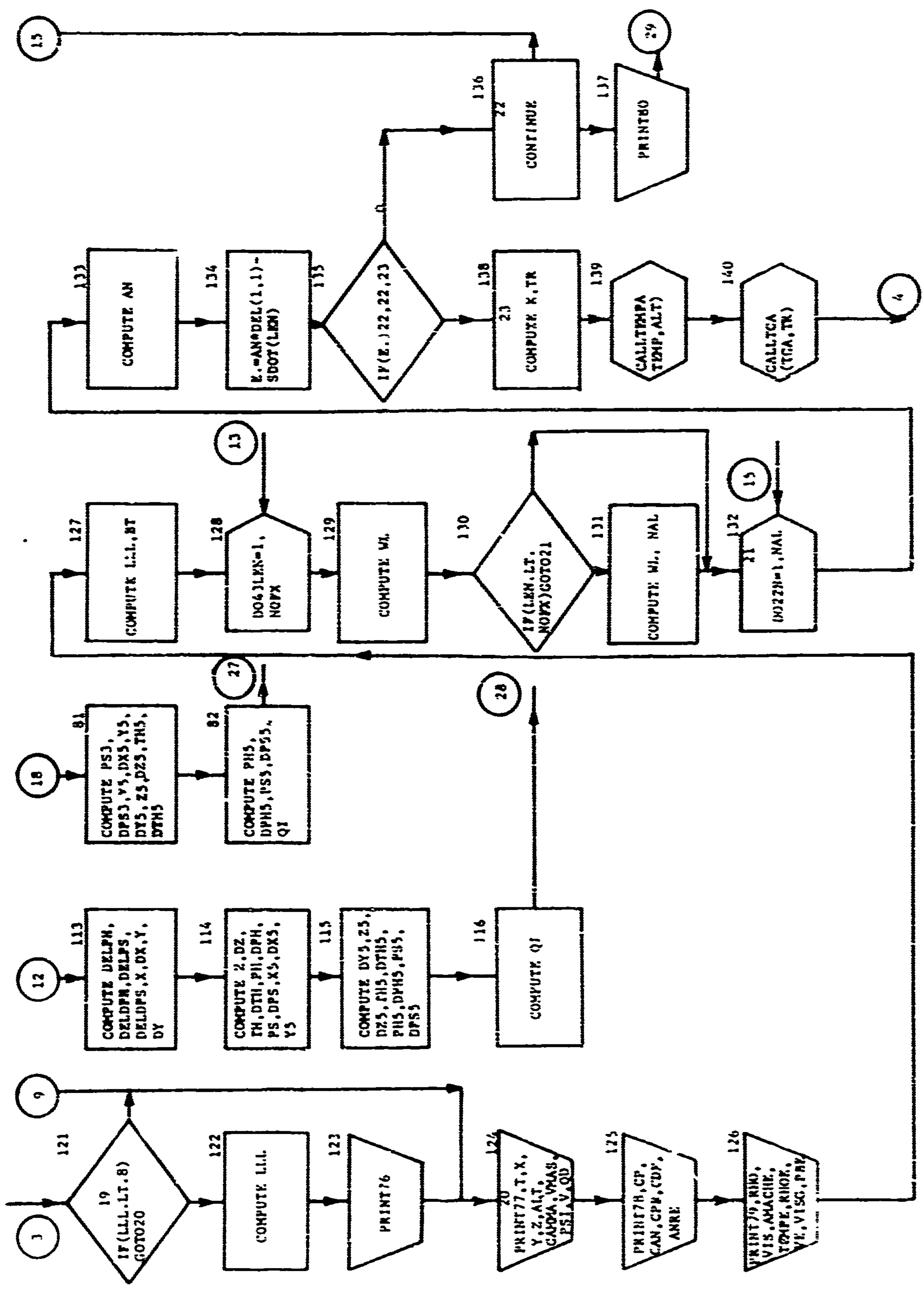
In addition to the printed output, selected quantities may also be obtained as punched output. The punched cards may be useful for machine plotting or as input to some other program.

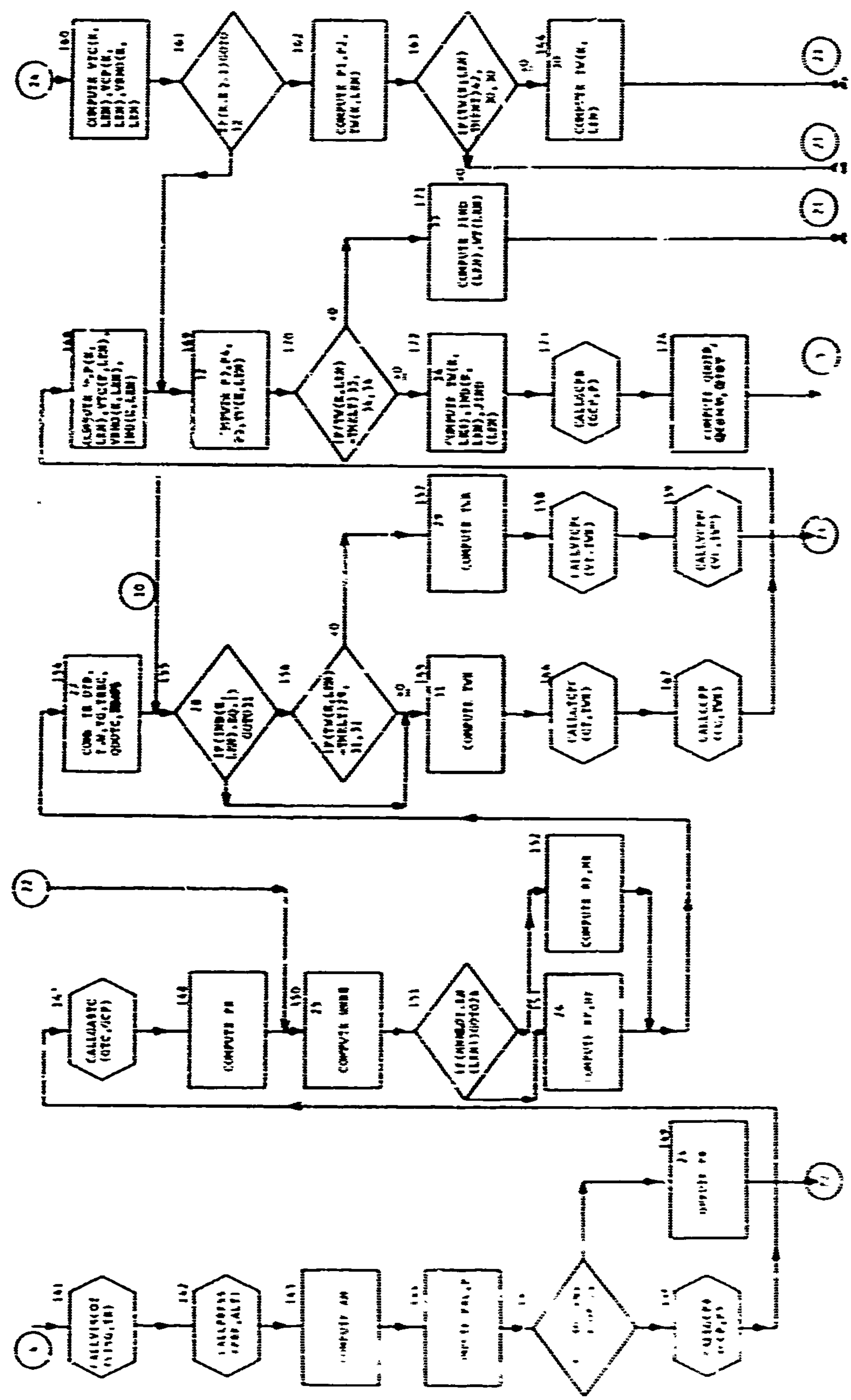
3. FLOW DIAGRAMS

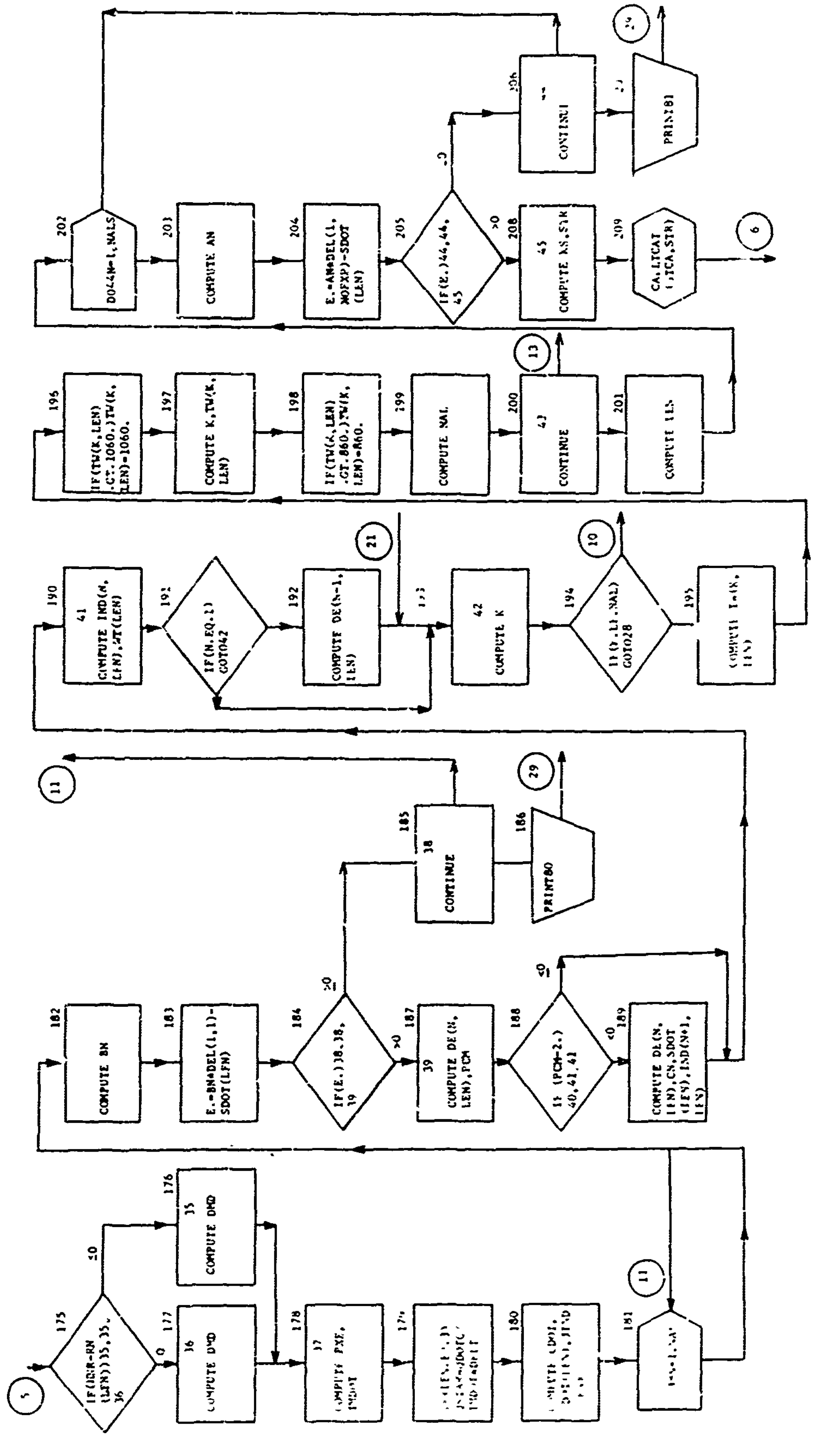


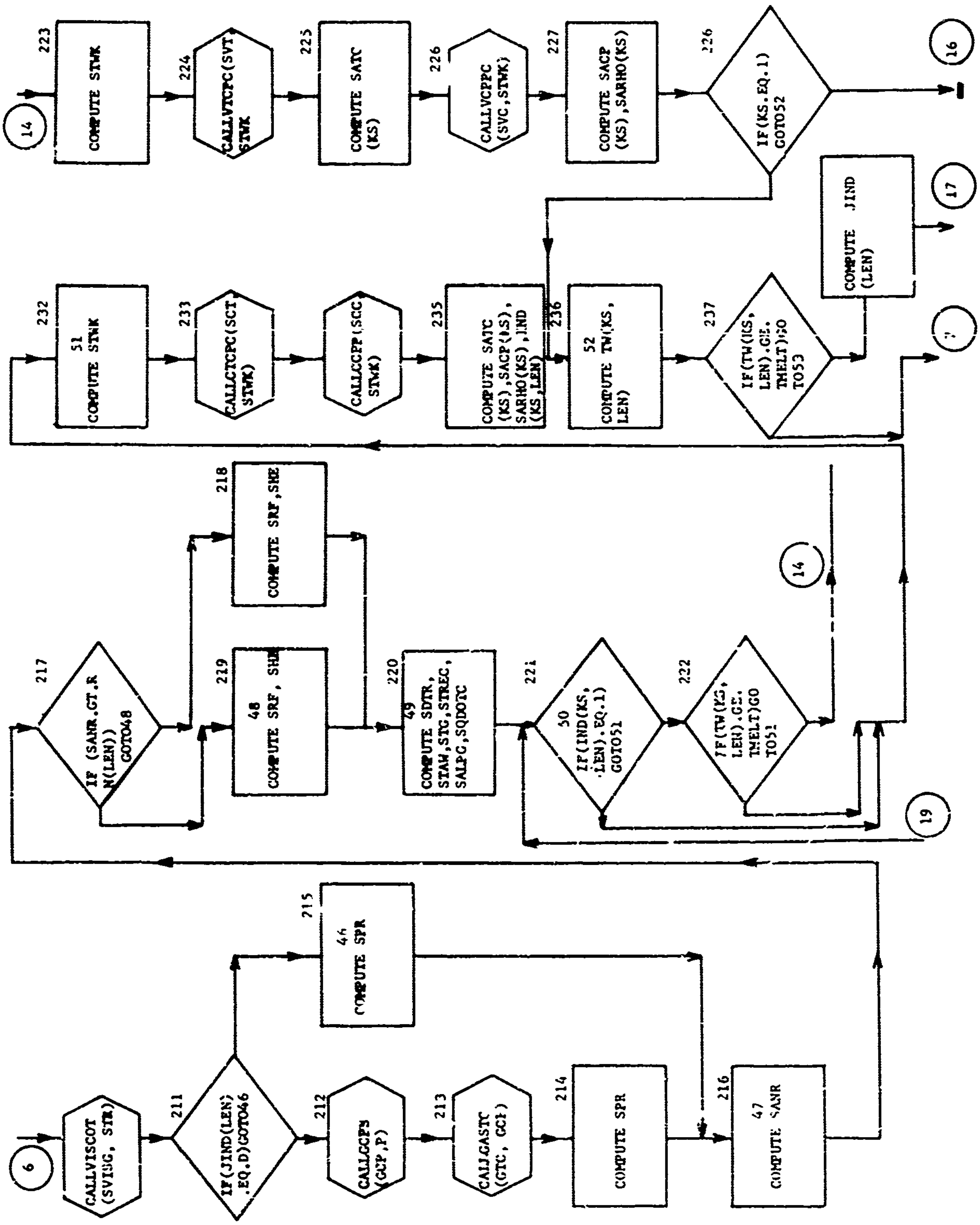




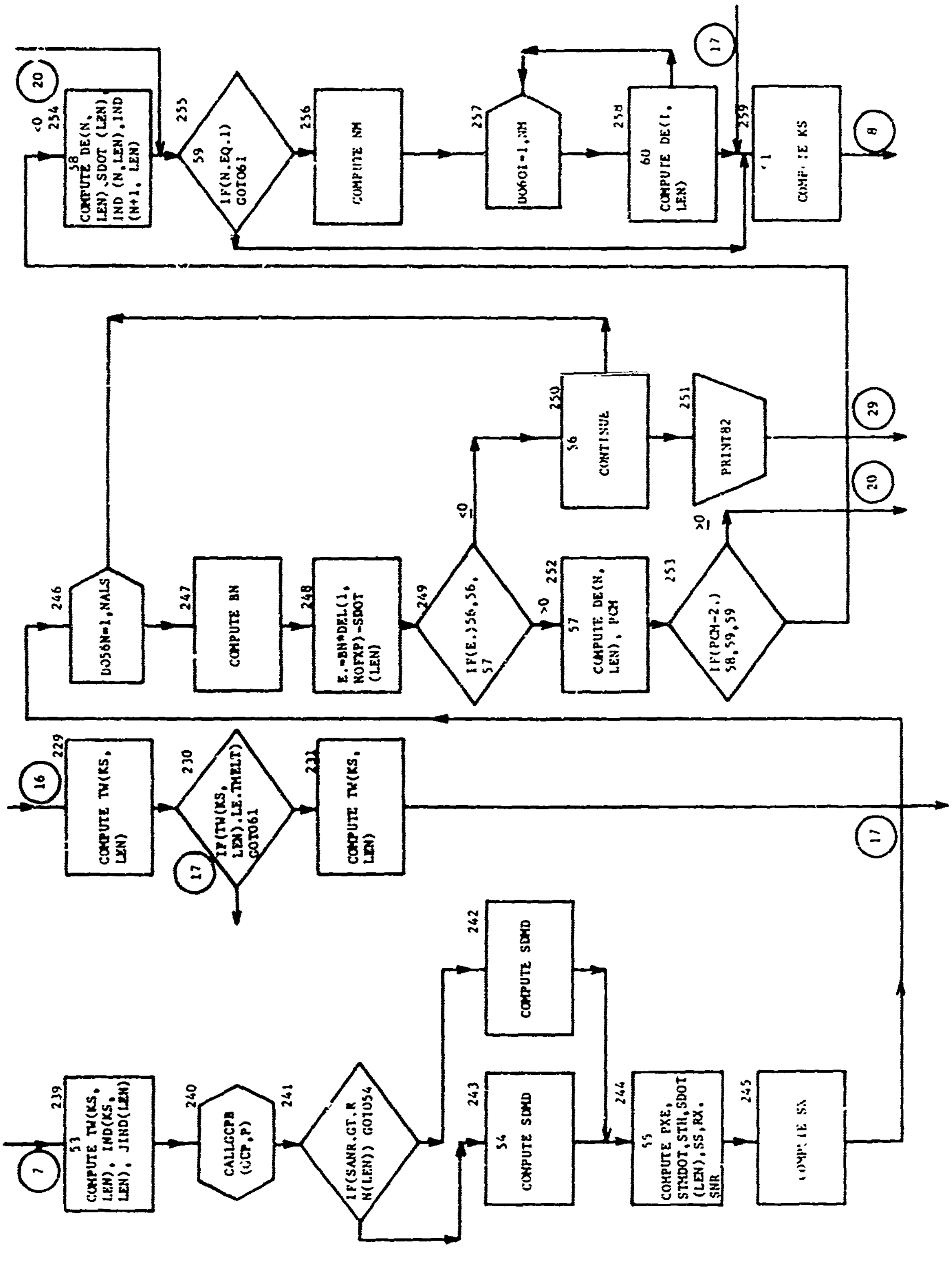

COMPUTE AN
K.=AN*DEL(1,1)-SDOT(LKN)
IF(K.)22,22,23
CONTINUE
PRINT80
COMPUTE K,TR
CALLTEMPA(TEMP,ALT)
CALLTCA(TGA,TR)
COMPUTE LLL,NT
DO431LKN=1,NOPX
COMPUTE WL
IF(LKN.LT.NOPX)GOTO21
COMPUTE WL, NAL
DO22N=1,NAL
COMPUTE PS3,DPS3,Y5,DX5,Y5,DY5,Z5,DZ5,TH5,DTH5
COMPUTE PH5,DPH5,PS5,DPS5,QI
COMPUTE DELPH,DELDPH,DELPS,DELDPS,X,DX,Y,DY
COMPUTE Z,DZ,TH,DTH,PH,DPH,PS,DPS,X5,DX5,Y5
COMPUTE DY5,Z5,DZ5,TH5,DTH5,PH5,DPH5,PS5,DPS5
COMPUTE QI
IF(LLL.LT.8)GOTO20
COMPUTE LLL
PRINT76
PRINT77,T,X,Y,Z,ALT,GAMMA,VMAS,PSI,V,QD
PRINT78,CP,CAN,CPM,CDY,ANRE
PRINT79,RHO,VIS,AMACHR,TEMPE,RHOE,VE,VISG,PRE

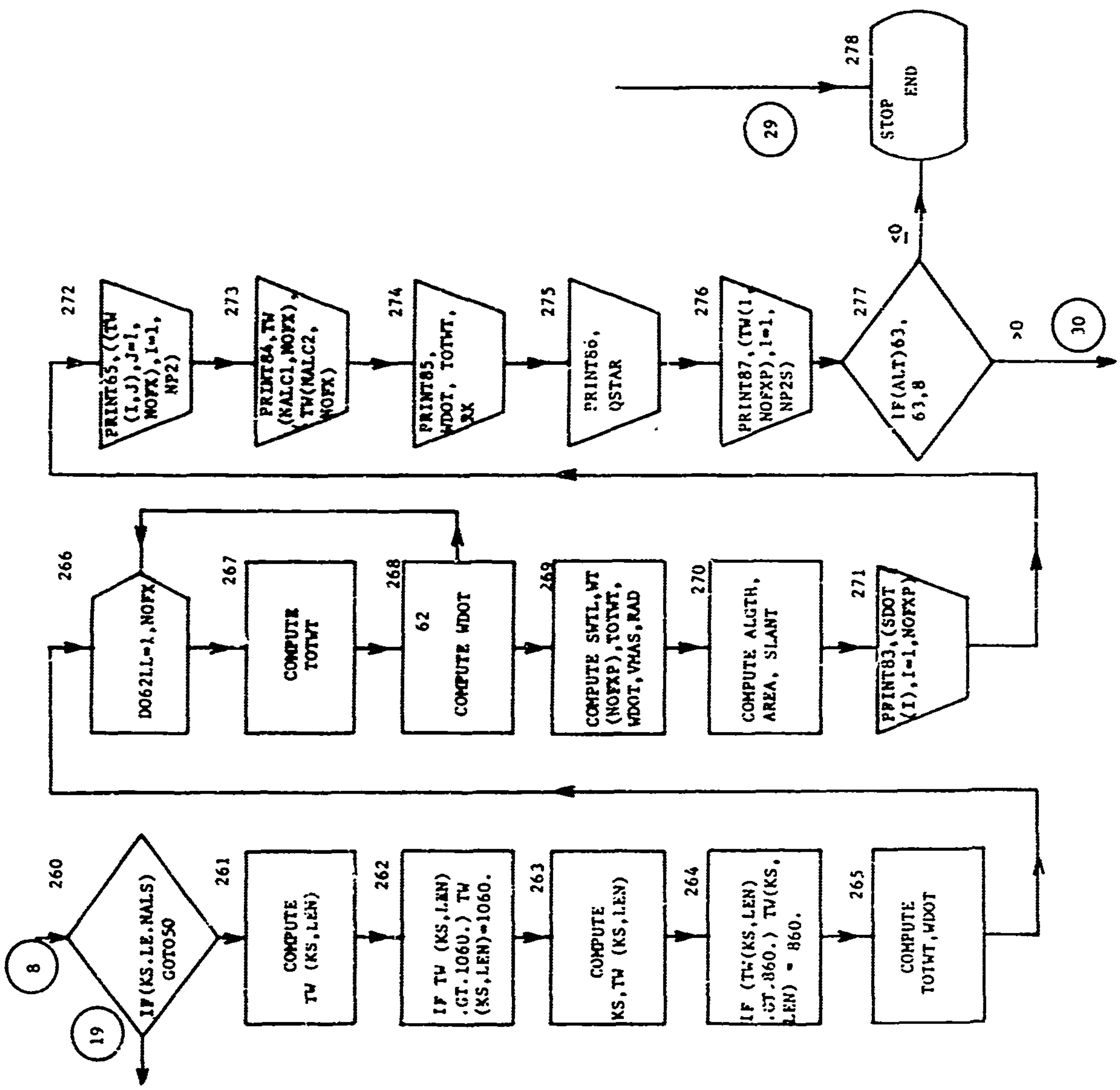



COMPUTE DMD
COMPUTE BN
E.-BN*DEL(1,1)-SDOT(LEN)
IF(E.)38,38,39
CONTINUE
PRINT80
COMPUTE DE(N,LEN),PCM
COMPUTE IND(N,LEN),WT(LEN)
IF(N.EQ.1)GOTO42
COMPUTE K
COMPUTE K,TW(K,LEN)
COMPUTE NAL
CONTINUE
COMPUTE AN
E.-AN*DEL(1,NOFXP)-SDOT(LEN)
IF(E.)44,44,45
CONTINUE
PRINT81
COMPUTE KS,STR



14
223
COMPUTE STWK
224
CALLVTCPC(SVT STWK
225
COMPUTE SATC (KS)
226
CALLVCPPC (SVC,STWK)
227
COMPUTE SACP (KS),SARHO(KS)
226
IF(KS.EQ.1) GOTO52
16
232
51 COMPUTE STWK
233
CALLCTCPC(SCT STWK)
CALLCCPP(SCC STWK)
235
COMPUTE SATC (KS),SACP(KS), SARHO(KS),IND (KS,LEN)
236
52 COMPUTE TW(KS, LEN)
237
IF(TW(KS, LEN).GE. TMELT)GO TO53
COMPUTE JIND (LEN)
17
217
IF (SANR.GT.R M(LEN)) GOTO48
218
COMPUTE SRF,SHE
219
48 COMPUTE SRF, SHE
220
49 COMPUTE SDTR, STAW,STG,STREC, SALPG,SQDOTC
221
50 IF(IND(KS, LEN).EQ.1) GOTO51
222
IF(TW(KS, LEN).GE. TMELT)GO TO51
14
19
6
CALLVISCOT (SVISG, STR)
211
IF(JIND(LEN) .EQ.0)GOTO46
212
CALLGCPS (GCP,P)
213
CALLGASTC (GTC, GCP)
214
COMPUTE SPR
215
46 COMPUTE SPR
216
47 COMPUTE SANR


COMPUTE TW(KS, LEN), IND(KS, LEN), JIND(LEN)
CALLGCPB (GCP,P)
IF(SANR.GT.R N(LEN)) GOTO54
COMPUTE SDMD
COMPUTE SDMD
COMPUTE PXE, STHDOT,STH,SDOT (LEN),SS,RX, SNR
COMPUTE TW(KS, LEN)
IF(TW(KS, LEN).LE.TMELT) GOTO61
COMPUTE TW(KS, LEN)
DO56N=1,NALS
COMPUTE BN
E.=BN*DEL(1, NOFXP)-SDOT (LEN)
IF(E.)56,56, 57
COMPUTE DE(N, LEN), PCM
IF(PCM-2.) 58,59,59
CONTINUE
PRINT82
COMPUTE DE(N, LEN),SDOT (LEN) IND (N,LEN),IND (N+1, LEN)
IF(N.EQ.1) GOTO61
COMPUTE NM
DO60I=1,NM
COMPUTE DE(I, LEN)
COMPUTE KS


8
19
260
IF(KS.LE.NALS) GOTO50
261
COMPUTE TW (KS,LEN)
262
IF TW (KS,LEN) .GT.1060.) TW (KS,LEN)=1060.
263
COMPUTE KS,TW (KS,LEN)
264
IF (TW(KS,LEN) .GT.860.) TW(KS, LEN) = 860.
265
COMPUTE TOTWT,WDOT
266
DO62LL=1,NOFX
267
COMPUTE TOTWT
268
62
COMPUTE WDOT
269
COMPUTE SWTL,WT (NOFXP),TOTWT, WDOT,VMAS,RAD
270
COMPUTE ALGTH, AREA, SLANT
271
PRINT83,(SDOT (I),I=1,NOFXP)
272
PRINT65,((TW (I,J),J=1, NOFX),I=1, NP2)
273
PRINT84,TW (NALC1,NOFX), TW(NALC2, NOFX)
274
PRINT85, WDOT, TOTWT, RX
275
PRINT86, QSTAR
276
PRINT87,(TW(I, NOFXP),I=1, NP2S)
277
IF(ALT)63, 63,8
≤0
>0
30
29
278
STOP END

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APPENDIX I

STRAB-6 PROGRAM LISTING

```
      PROGRAM STRAB62 (INPUT,OUTPUT)
C     6 DEGREE TRAJECTORY WITH ABLATION HEATING AND STAG
      COMMON /A/ RE
      COMMON /B/ AREA,RAD,SLANT,SNR,THETC,V
      COMMON /C/ CPM,CP,CAN,CPB,CDF
      COMMON /D/ TW(50,12),IND(50,12),JIND(12),VCP(50,12),VTC(50,12),VPH
     1O(50,12),DEL(50,12),DE(50,12),SDOT(12),XI(12),RS(12),RL(12),SOL(12
     2),WT(12),TM(12),TWT(12),SACP(50),SATC(50),SARHO(50),RN(12),QSTR(12
     3),QDOTC(12),QTOT(12),QCOND(12)
      COMMON /E/ NOFXM,NAL,ALT,AMACH,QD,AMACHE,TEMPE,RHOE,VE,VISG,PBE,AN
     1RE
      COMMON /F/ NOFX,ALGTH,RADI,POS(11),AZN,GLAT
C     VEHICLE DATA
C     IF NOFX IS CHANGED CHANGE FORMAT 103
C     IF CONE ANGLE IS CHANGED SUB CDSF MUST BE CHANGED
      DATA SNR,THETC,BI,SM/.0208,.07853,6.27836,.59718/
      DATA PI,E,AJ,GRAV,G/3.14159,2.7183,778.,32.174,32.174/
      DATA REQ,PE,ET,WE/20.927491E+06,.673852E-02,.08181333,0.7292E-04/
      DATA NOFX,NAL,NALC,NALS/8,4,10,35/
      DATA DELT,DT,H,BT,AT/.05,.0005,.001,.05,1./
      DATA AZN,GLAT,DLON,GAMMA/154.,33.996,-107.5,-22.39/
      DATA V,Z,ALPHA/15167.,2.50E+05,7./
      DATA (POS(I),I=1,8)/6.607,18.570,30.533,42.496,54.459,66.422,78.38
     15,86.469/
      AIZ=0.51
      AIX=23.08
      CALL INITIAL (SNR,THETC,SLANT)
      ALGTHI=ALGTH
      SNRI=SNR
      CLAT1=ATAN((1.-ET**2)*TAN(GLAT))
      CLAT=CLAT1*180./PI
      ETA1=GLAT-CLAT1
      PHN=(90.-GAMMA-ALPHA)*PI/180.
      PPH=0.0
      PH=(1.+PPH)*PHN
      DLGG=DLON
      PH1=PH
      VMAS=BI
      RAD=RADI
      NOFXP=NOFX+1
      NOFXM=NOFX-1
      AKL1=5370.
      AKT1=4240.
      AKL2=5.37
      AKT2=5.77
      GVIS=4.429E-5
      TOL=.00854
      TMELT=6760.
      TEM=544.
      NALT=NAL
      NP1=NAL+1
      NP2=NAL+2
      NALC1=NALC+1
      NALC2=NALC+2
      NP1S=NALS+1
      NP2S=NALS+2
      RHOV=90.4
      RHOC=74.
      ATJRHO=120.96
      CPA=.2395
      DO 1 J=1,NOFXP
```

```
      JIND(J)=0
    1 SDOT(J)=0.
      DO 2 J=1,NOFXM
      VCP(NP1,J)=.315
      VCP(NP2,J)=.208
      VTC(NP1,J)=.74E-04
      VTC(NP2,J)=.03694
      VRHO(NP1,J)=91.7
      VRHO(NP2,J)=169.
      DO 2 I=1,NP2
      TW(I,J)=TEM
    2 IND(I,J)=0
      DO 3 I=1,NAL
      DO 3 J=1,NOFXM
      DEL(I,J)=TOL
    3 DE(I,J)=TOL
      DO 4 I=1,NOFXM
      DEL(NP1,I)=.00333
      DE(NP1,I)=.00333
      DEL(NP2,I)=.005
    4 DE(NP2,I)=.005
      DO 5 I=1,NALS
      IND(I,NOFXP)=0
      DEL(I,NOFXP)=TOL
    5 DE(I,NOFXP)=TOL
      TEMP=298.2
      TAW=TEMP
      PHI=80.967
      STAW=TEMP
      STOL=TOL
      SX=.01745*RS(NOFXP)*PHI
      RX=SNR
      VCP(NALC1,NOFX)=.315
      VCP(NALC2,NOFX)=.208
      VTC(NALC1,NOFX)=.74E-04
      VTC(NALC2,NOFX)=.03694
      VRHO(NALC1,NOFX)=91.7
      VRHO(NALC2,NOFX)=169.
      DO 6 I=1,NALC2
      TW(I,NOFX)=TEM
      IND(I,NOFX)=0
      DEL(I,NOFX)=TOL
    6 DE(I,NOFX)=TOL
      DEL(NALC1,NOFX)=.00333
      DE(NALC1,NOFX)=.00333
      DEL(NALC2,NOFX)=.005
      DE(NALC2,NOFX)=.005
      DE(NP2S,NOFXP)=.005
      DEL(NP2S,NOFXP)=.005
      DE(NP1S,NOFXP)=.00333
      DEL(NP1S,NOFXP)=.00333
      SACP(NP1S)=.315
      SACP(NP2S)=.208
      SATC(NP1S)=.74E-04
      SATC(NP2S)=.03694
      SARHO(NP1S)=91.7
      SARHO(NP2S)=169.
      DO 7 N=1,NP2S
    7 TW(N,NOFXP)=TEM
      PSI=0.
      DAZ=0.0
      AZ=(1.000+DAZ)*AZN
```

```
      SGLAT=SIN(GLAT)
      CGLAT=COS(GLAT)
      SAZ=SIN(AZ)
      CAZ=COS(AZ)
      WEX=-WE*CGLAT*SAZ
      WEY=WE*CGLAT*CAZ
      WEZ=WE*SGLAT
      RE1=REQ/(1.000+PE*(SIN(CLAT1))**2)**.500
      RE=RE1
      RXH=RE1*SIN(ETA1)*SAZ
      RYH=-RE1*SIN(ETA1)*CAZ
      RZH=RE1*COS(ETA1)
      T=0.0
      X=0.0
      DX=0.0
      Y=0.0
      PPH=0.0
      PH=(1.0+PPH)*PHN
      DZ=V*SIN(GAMMA*PI/180.)
      DY=V*COS(GAMMA*PI/180.)
      LLL=0
      ALT=Z
      TH=0.0
      DTH=0.0
      DPH=0.0
      PS=0.0
      DELPS=0.0
      DPSN=2.*PI
      DPS=(1.+DELPS)*DPSN
      U=0.1407639E+17
      BJ=1623.41E-06
      BH=6.04E-06
      BK=6.37E-06
      AREA=PI*RAD**2
      DIA=1.781
      DCD=0.00
      D2X=0.0
      D2Y=0.0
      D2Z=0.0
      D2TH=0.0
      D2PH=0.0
      D2PS=0.0
      PRINT 71
      PRINT 72, (JIND(I),I=1,NOFXP)
      PRINT 92, (SDOT(I),I=1,NOFXP)
      PRINT 73, ((IND(I,J),J=1,NOFX),I=1,NALC2)
      PRINT 74, ((VCP(I,J),J=1,NOFX),I=1,NALC2)
      PRINT 75, ((VTC(I,J),J=1,NOFX),I=1,NALC2)
      PRINT 76, ((VRHO(I,J),J=1,NOFX),I=1,NALC2)
      PRINT 77, ((DEL(I,J),J=1,NOFX),I=1,NALC2)
      PRINT 78, ((DE(I,J),J=1,NOFX),I=1,NALC2)
      PRINT 79, ((TW(I,J),J=1,NOFX),I=1,NALC2)
      PRINT 71
      PRINT 80
      CALL VSD (VS,ALT)
      CALL RHOF (RHO,ALT)
      AMACH=V/VS
      CALL VISCO (VIS,ALT)
      ANR=RHO*V*SLANT/VIS
      CALL CDSF (CD,AMACH,ANR)
      QD=.5*RHO*V**2
      ALPT=ABS(ALPHA)
```

```
      PRINT 81, T,X,Y,Z,ALT,GAMMA,VMAS,PSI,V,QD,AMACH,CD,ANR,PH1,THE,ALP
     1,BET,PS,ALPT,XE,YE,ZE,FD,FN,GFZ,CLAT,DLON,ABETA,GCIR,AIZ,AIX
      LLL=LLL+1
      GO TO 9
8     D2X=FX/VMAS-2.*DA-C*WEY+B*WEZ+GX
      D2Y=FY/VMAS-2.*DB-A*WEZ+C*WEY+GY
      D2Z=FZ/VMAS-2.*DC-B*WEX+A*WEY+GZ
      D2TH=TY/AIX-WX2*DZ2+AIZ*WZ2*DX2/AIX-DWEY2
      D2PH=(-TX/AIX+AIZ*WZ2*DY2/AIX-WY2*DZ2+DPH*DTH*SIN(TH)+DWEX2)/COS(T
     1H)
      D2PS=TZ/AIZ-AIX*WY2*DX2/AIZ+AIX*WX2*DY2/AIZ+D2PH*SIN(TH)+DPH*DTH*C
     1OS(TH)-DWEZ2
      CALL CDSF (CD,AMACH,ANR)
      PER=1.+.0375*ALPT+.00156*ALPT**2.
      CD=CD*PER
9     X1=X+DX*H/2.
      DX1=DX+D2X*H/2.
      Y1=Y+DY*H/2.
      DY1=DY+D2Y*H/2.
      Z1=Z+DZ*H/2.
      DZ1=DZ+D2Z*H/2.
      TH1=TH+DTH*H/2.
      DTH1=DTH+D2TH*H/2.
      PH1=PH+DPH*H/2.
      DPH1=DPH+D2PH*H/2.
      PS1=PS+DPS*H/2.
      DPS1=DPS+D2PS*H/2.
      X5=X1
      DX5=DX1
      Y5=Y1
      DY5=DY1
      Z5=Z1
      DZ5=DZ1
      TH5=TH1
      DTH5=DTH1
      PH5=PH1
      DPH5=DPH1
      PS5=PS1
      DPS5=DPS1
      QI=1.000
      GO TO 12
10    D2X1=FX/VMAS-2.*DA-C*WEY+B*WEZ+GX
      D2Y1=FY/VMAS-2.*DB-A*WEZ+C*WEX+GY
      D2Z1=FZ/VMAS-2.*DC-B*WEX+A*WEY+GZ
      D2TH1=TY/AIX-WX2*DZ2+AIZ*WZ2*DX2/AIX-DWEY2
      D2PH1=(-TX/AIX+AIZ*WZ2*DY2/AIX-WY2*DZ2+DPH5*DTH5*STH5+DWEX2)/CTH5
      D2PS1=TZ/AIZ-AIX*WY2*DX2/AIZ+AIX*WX2*DY2/AIZ+D2PH1*STH5+DPH5*DTH5*
     1CTH5-DWEZ2
      X2=X+DX1*H/2.
      DX2=DX+D2X1*H/2.
      Y2=Y+DY1*H/2.
      DY2=DY+D2Y1*H/2.
      Z2=Z+DZ1*H/2.
      DZ2=DZ+D2Z1*H/2.
      TH2=TH+DTH1*H/2.
      DTH2=DTH+D2TH1*H/2.
      PH2=PH+DPH1*H/2.
      DPH2=DPH+D2PH1*H/2.
      PS2=PS+DPS1*H/2.
      DPS2=DPS+D2PS1*H/2.
      X5=X2
      DX5=DX2
```

```
      Y5=Y2
      DY5=DY2
      Z5=Z2
      DZ5=DZ2
      TH5=TH2
      DTH5=DTH2
      PH5=PH2
      DPH5=DPH2
      PS5=PS2
      DPS5=DPS2
      QI=2.000
      GO TO 13
 11   D2X2=FX/VMAS-2.*DA-C*WEY+B*WEZ+GX
      D2Y2=FY/VMAS-2.*DB-A*WEZ+C*WEX+GY
      D2Z2=FZ/VMAS-2.*DC-B*WEX+A*WEY+GZ
      D2TH2=TY/AIX-WX2*OZ2+AIZ*WZ2*OX2/AIX-DWEY2
      D2PH2=(-TX/AIX+AIZ*WZ2*OY2/AIX-WY2*OZ2+DPH5*DTH5*STH5+DWEX2)/CTH5
      D2PS2=TZ/AIZ-AIX*WY2*OX2/AIZ+AIX*WX2*OY2/AIZ+D2PH2*STH5+DPH5*DTH5*
     1CTH5-DWEZ2
      X3=X+DX2*H/2.
      DX3=DX+D2X2*H/2.
      Y3=Y+DY2*H/2.
      DY3=DY+D2Y2*H/2.
      Z3=Z+DZ2*H/2.
      DZ3=DZ+D2Z2*H/2.
      TH3=TH+DTH2*H/2.
      DTH3=DTH+D2TH2*H/2.
      PH3=PH+DPH2*H/2.
      DPH3=DPH+D2PH2*H/2.
      PS3=PS+DPS2*H/2.
      DPS3=DPS+D2PS2*H/2.
      X5=X3
      DX5=DX3
      Y5=Y3
      DY5=DY3
      Z5=Z3
      DZ5=DZ3
      TH5=TH3
      DTH5=DTH3
      PH5=PH3
      DPH5=DPH3
      PS5=PS3
      DPS5=DPS3
      QI=3.000
 12   T=T+DT
 13   R=SQRT((RXH+X5)**2+(RYH+Y5)**2+(RZH+Z5)**2)
      ZE=(RZH+Z5)*SGLAT-CGLAT*((RXH+X5)*SAZ-(RYH+Y5)*CAZ)
      AL=ASIN(ZE/R)
      CAL=COS(AL)
      SAL=SIN(AL)
      CLAT=AL*180./PI
      RE=REQ/(1.000+PE*SAL**2)**.500
      ALT=R-RE
      YE=(RXH+X5)*CAZ+(RYH+Y5)*SAZ
      XE=(RZH+Z5)*CGLAT+SGLAT*((RXH+X5)*SAZ-(RYH+Y5)*CAZ)
      CALL LONG (DLG,XE,YE,PI)
      CLG=COS(DLG)
      SLG=SIN(DLG)
      DLON=DLGG+DLG*180./PI
      GCIR=((RE+RE1)/2.)*ACOS(SAL*SIN(CLAT1)+CAL*COS(CLAT1)*COS(AL-CLAT1
     1))
      G11=-SGLAT*CAL*CLG+CGLAT*SAL
```

```
      G12=SGLAT*SAL*CLG+CGLAT*CAL
      G21=-CAL*SLG
      G22=SAL*SLG
      G31=-CGLAT*CAL*CLG-SGLAT*SAL
      G32=+CGLAT*SAL*CLG-SGLAT*CAL
      P12=1.-3.*SAL**2
      P13=3.*SAL-5.*SAL**3
      P14=3.-30.*SAL**2+35.*SAL**4
      P15=SIN(2.*AL)
      P6=CAL*(1.-5.*SAL**2)
      P7=SAL*CAL*(-3.+7.*SAL**2)
      GR=+U/R**2*(1.+BJ*(REQ/R)**2*P12+4./5.*BH*(REQ/R)**3*P13+BK/6.*(RE
     1Q/R)**4*P14)
      SL=U/R**2*(-BJ*(REQ/R)**2*P15+3./5.*BH*(REQ/R)**3*P6+2./3.*BK*(REQ
     1/R)**4*P7)
      GX=GR*(G11*SAZ+G21*CAZ)+GL*(G12*SAZ+G22*CAZ)
      GY=GR*(G21*SAZ-G11*CAZ)+GL*(G22*SAZ-G12*CAZ)
      GZ=GR*G31+GL*G32
      CPS5=COS(PS5)
      SPS5=SIN(PS5)
      STH5=SIN(TH5)
      CTH5=COS(TH5)
      SPH5=SIN(PH5)
      CPH5=COS(PH5)
      A11=CPS5*CTH5
      A12=SPS5*CPH5-STH5*SPH5*CPS5
      A13=-CPS5*STH5*CPH5-SPS5*SPH5
      A21=-SPS5*CTH5
      A22=SPS5*STH5*SPH5+CPS5*CPH5
      A23=SPS5*STH5*CPH5-SPH5*CPS5
      A31=STH5
      A32=CTH5*SPH5
      A33=CTH5*CPH5
      A=WEY*(RZH+Z5)-(RYH+Y5)*WEZ
      B=WEZ*(RXH+X5)-(RZH+Z5)*WEX
      C=WEX*(RYH+Y5)-(RXH+X5)*WEY
      DA=DZ5*WEY-DY5*WEZ
      DB=DX5*WEZ-DZ5*WEX
      DC=DY5*WEX-DX5*WEY
      B11=CTH5
      B12=-STH5*SPH5
      B13=-STH5*CPH5
      B21=0.
      B22=CPH5
      B23=-SPH5
      B31=STH5
      B32=CTH5*SPH5
      B33=CTH5*CPH5
      DB11=-DTH5*STH5
      DB12=-DTH5*CTH5*SPH5-DPH5*CPH5*STH5
      DB13=-DTH5*CTH5*CPH5+DPH5*SPH5*STH5
      DB21=0.
      DB22=-DPH5*SPH5
      DB23=-DPH5*CPH5
      DB31=DTH5*CTH5
      DB32=DPH5*CPH5*CTH5-DTH5*STH5*SPH5
      DB33=-DTH5*STH5*CPH5-DPH5*SPH5*CTH5
      WEX2=B11*WEX+B12*WEY+B13*WEZ
      WEY2=B21*WEX+B22*WEY+B23*WEZ
      WEZ2=B31*WEX+B32*WEY+B33*WEZ
      DWEX2=DB11*WEX+DB12*WEY+DB13*WEZ
      DWEY2=DB21*WEX+DB22*WEY+DB23*WEZ
```

```
      DWEZ2=DB31*WEX+DB32*WEY+DB33*WEZ
      WX2=WEX2-DPH5*CTH5
      WY2=WEY2+DTH5
      WZ2=WEZ2+DPS5-DPH5*STH5
      OX2=WX2
      OY2=WY2
      OZ2=WEZ2-DPH5*STH5
      VRX=DX5
      VRY=DY5
      VRZ=DZ5
      VR=SQRT(VRX**2+VRY**2+VRZ**2)
      V=SQRT(DX5**2+DY5**2+DZ5**2)
      CALL RHOF (RHO,ALT)
      CALL VISCO (VIS,ALT)
      QD=.5*RHO*V**2
      CALL VSD (VS,ALT)
      AMACH=V/VS
      ANR=RHO*V*SLANT/VIS
      VRX4=A11*VRX+A12*VRY+A13*VRZ
      VRY4=A21*VRX+A22*VRY+A23*VRZ
      VRZ4=A31*VRX+A32*VRY+A33*VRZ
      WX3=-DPH5*CTH5*CPS5+DTH5*SPS5
      WY3=DPH5*CTH5*SPS5+DTH5*CPS5
      WZ3=DPS5-DPH5*STH5
      CALL ATTK (VRZ4,VRY4,ALP,PI)
      CALL SSLP (VRZ4,VRX4,BET,PI)
      ALPT=ABS(ALP)
      ALPT=ALPT*180./PI
      ALP=ALP*180./PI
      BET=BET*180./PI
      ALP1=ABSF(ALP)
      BET1=ABSF(BET)
      CALL ACMQ (CMQ,AMACH)
      CALL ACNA (CNA,AMACH)
C     CNA PER DEGREE
C     CMQ PER RADIAN
      CNR=CMQ
      CMA=-SM*CNA/DIA
      CM=CMA*ALP+CMQ*WX3*DIA/(2.*V)
      TM=CM*QD*AREA*DIA
      FN=CNA*QD*AREA*ALP
      CNB=-CMA
      CYB=-CNA
      CN=CNB*BET+CNR*WY3*DIA/(2.*V)
      TN=CN*QD*AREA*DIA
      FY1=CYB*QD*AREA*BET
      TL=0.
      FD=CD*QD*AREA
      FX3=FY1
      FY3=-FN
      FZ3=-FD
      GFX=FX3/(VMAS*GRAV)
      GFY=(FY3-VMAS*GRAV*SIN(PH))/(VMAS*GRAV)
      GFZ=(FZ3+VMAS*GRAV*COS(PH))/(VMAS*GRAV)
      ABETA=VMAS*GRAV/(CD*AREA)
      FX=A11*FX3+A21*FY3+A31*FZ3
      FY=A12*FX3+A22*FY3+A32*FZ3
      FZ=A13*FX3+A23*FY3+A33*FZ3
      TX3=TM
      TY3=TN
      TZ3=TL
      TX=TX3*CPS5-TY3*SPS5
```

```
      TY=TX3*SPS5+TY3*CPS5
      TZ=TZ3
      IF (4.000-QI) 15,18,14
14    IF (1.000-QI) 16,10,15
15    GO TO 69
16    IF (2.000-QI) 17,11,15
17    D2X3=FX/VMAS-2.*DA-C*WEY+B*WEZ+GX
      D2Y3=FY/VMAS-2.*DB-A*WEZ+C*WEX+GY
      D2Z3=FZ/VMAS-2.*DC-B*WEX+A*WEY+GZ
      D2TH3=TY/AIX-WX2*OZ2+AIZ*WZ2*OX2/AIX-DWEY2
      D2PH3=(-TX/AIX+AIZ*WZ2*OY2/AIX-WY2*OZ2+DPH5*DTH5*STH5+DWEX2)/CTH5
      D2PS3=TZ/AIZ-AIX*WY2*OX2/AIZ+AIX*WX2*OY2/AIZ+D2PH3*STH5+DPH5*DTH5*
     1CTH5-DWEZ2
      DELX=H/6.*(DX+2.*DX1+2.*DX2+DX3)
      DELDX=H/6.*(D2X+2.*D2X1+2.*D2X2+D2X3)
      DELY=H/6.*(DY+2.*DY1+2.*DY2+DY3)
      DELDY=H/6.*(D2Y+2.*D2Y1+2.*D2Y2+D2Y3)
      DELZ=H/6.*(DZ+2.*DZ1+2.*DZ2+DZ3)
      DELDZ=H/6.*(D2Z+2.*D2Z1+2.*D2Z2+D2Z3)
      DELTH=H/6.*(DTH+2.*DTH1+2.*DTH2+DTH3)
      DELDTH=H/6.*(D2TH+2.*D2TH1+2.*D2TH2+D2TH3)
      DELPH=H/6.*(DPH+2.*DPH1+2.*DPH2+DPH3)
      DELDPH=H/6.*(D2PH+2.*D2PH1+2.*D2PH2+D2PH3)
      DELPS=H/6.*(DPS+2.*DPS1+2.*DPS2+DPS3)
      DELDPS=H/6.*(D2PS+2.*D2PS1+2.*D2PS2+D2PS3)
      X=X+DELX
      DX=DX+DELDX
      Y=Y+DELY
      DY=DY+DELDY
      Z=Z+DELZ
      DZ=DZ+DELDZ
      TH=TH+DELTH
      DTH=DTH+DELDTH
      PH=PH+DELPH
      DPH=DPH+DELDPH
      PS=PS+DELPS
      DPS=DPS+DELDPS
      X5=X
      DX5=DX
      Y5=Y
      DY5=DY
      Z5=Z
      DZ5=DZ
      TH5=TH
      DTH5=DTH
      PH5=PH
      DPH5=DPH
      PS5=PS
      DPS5=DPS
      QI=4.000
      GO TO 13
18    THE=TH*180./PI
      PH1=PH*180./PI
      GAMMA=ATAN(DZ5/DY5)*180./PI
      PSI=ATAN(DX5/DY5)*180./PI
      BTL=BT-H/6.
      BTH=BT+H/6.
      IF (ALT.LE.0.0) GO TO 20
      IF (T.GT.BTL.AND.T.LT.BTH) GO TO 19
      GO TO 8
19    BT=BT+.05
C     ***********************************************************************
```

```
C     **************************************************************
20    WL=0.0
      DO 49 LEN=1,NOFX
      WL=WL+SCL(LEN)
      IF (LEN.LT.NOFX) GO TO 21
      WL=.25
      NAL=NALC
21    DO 22 N=1,NAL
      AN=N
      IF (AN*DEL(1,1)-SDOT(LEN)) 22,22,23
22    CONTINUE
      PRINT 84
      GO TO 69
23    K=N
      IF (LEN.GE.NOFX) TMELT=6400.
      TR=TEMPE+.58*(TW(K,LEN)-TEMPE)+.19*(TAW-TEMPE)
      CALL TEMPA (TEMP,ALT)
      CALL TCAT (TCA,TR)
      CALL VISCOT (VISE,TEMPE)
      CALL VISCOT (VISG,TR)
      CALL PRESS (PRE,ALT)
      AM=AMACH
      PBL=PRE*(1.+2.8*AM**2*(SIN(THETC))**2*(2.5+8.*AM*SIN(THETC))/(1.+1
     16.*AM*SIN(THETC)))
      P=PBL/2116.2
      IF (JIND(LEN).EQ.0) GO TO 24
C     ************ **************************************************
      CALL GCPB (GCP,P)
      IF (LEN.GE.NOFX) GCP=.4
C     **** **********************************************************
      CALL GASTC (GTC,GCP)
      PR=GCP*GVIS/GTC
      GO TO 25
24    PR=CPA*VISG/TCA
25    HNRE=RHOE*VE*WL/VISE*G
      RHOS=PBE/(1716.*TR)
      ANRR=RHOS*VE*WL/VISG*G
      IF (HNRE.GT.RN(LEN)) GO TO 26
      RF=PR**.5
      HE=.575*TCA/WL*PR**.33*HNRE**.5*(VISG/VISE*RHOS/RHOE)**.5
      GO TO 27
26    RF=PR**.33
      HE=.0296*TCA/WL*PR**.33*HNRE**.8*(VISG/VISE)**.2*(RHOS/RHOE)**.8
27    DTR=VE**2/(2.*G*AJ*CPA)
      TAW=TEMPE+RF*DTR
      QDOTC(LEN)=HE*(TAW-TW(K,LEN))
28    IF (IND(K,LEN).EQ.1) GO TO 33
      IF (TW(K,LEN)-TMELT) 29,33,33
29    TWK=TW(K,LEN)
      IF (LEN.GE.NOFX) GO TO 30
      CALL VTCPC (VT,TWK)
      CALL VCPPC (VC,TWK)
      VRHO(K,LEN)=RHOV
      GO TO 31
30    CALL TCATJ (VT,TWK)
      CALL CPATJ (VC,TWK)
      VRHO(K,LEN)=ATJRHO
31    VTC(K,LEN)=VT
      VCP(K,LEN)=VC
      IF (K.EQ.1) GO TO 36
      P1=VTC(K-1,LEN)*(TW(K-1,LEN)-TW(K,LEN))/(VRHO(K-1,LEN)*VCP(K-1,LEN
     1)*DE(K-1,LEN)**2)
```

```
      P2=VTC(K,LEN)*(TW(K,LEN)-TW(K+1,LEN))/(VRHO(K,LEN)*VCP(K,LEN)*DE(K
     1,LEN)**2)
      TW(K,LEN)=TW(K,LEN)+DELT*(P1-P2)
      IF (TW(K,LEN)-TMELT) 48,32,32
   32 TW(K,LEN)=TMELT-1.
      GO TO 48
   33 TWK=TW(K,LEN)
      IF (LEN.GE.NOFX) GO TO 34
      CALL CTCPC (CT,TWK)
      CALL CCPP (CC,TWK)
      VRHO(K,LEN)=RHOC
      GO TO 35
   34 CALL TCATJ (CT,TWK)
      CALL CPATJ (CC,TWK)
      VRHO(K,LEN)=ATJRHO
   35 VCP(K,LEN)=CC
      VTC(K,LEN)=CT
      IND(K,LEN)=1
   36 P3=DELT/(VCP(K,LEN)*VRHO(K,LEN)*DE(K,LEN))*2.
      P4=HE*(TAW-TW(K,LEN))
      P5=VTC(K,LEN)*(TW(K,LEN)-TW(K+1,LEN))/DE(K,LEN)
      HR=CPA*TEMPE+RF*VE**2/(2.*G*AJ)
      QCOND(LEN)=-VTC(K,LEN)*(TW(K,LEN)-TW(K+1,LEN))/DE(K,LEN)
      TW(K,LEN)=TW(K,LEN)+P3*(P4-P5)
      IF (TW(K,LEN)-TMELT) 37,38,38
   37 JIND(LEN)=0
      WT(LEN)=0.
      GO TO 48
   38 TW(K,LEN)=TMELT
      IND(K,LEN)=1
      JIND(LEN)=1
      CALL GCPB (GCP,P)
      IF (LEN.GE.NOFX) GCP=.4
      QDOTR=0.
      QTOT(LEN)=QDOTC(LEN)+QCOND(LEN)
      IF (QTOT(LEN).LE.0.0) GO TO 48
      IF (LEN.LT.NOFX) GO TO 39
      DELH=HR-CPA*TMELT
      QSTAR=2000.+2.*DELH
      CDOT=QTOT(LEN)/(QSTAR*ATJRHO)
      GO TO 43
   39 IF (HNRE-RN(LEN)) 40,40,41
   40 DMD=(QTOT(LEN))/(AKL1+AKL2*(HR-CPA*TMELT))
      GO TO 42
   41 DMD=(QTOT(LEN))/(AKT1+AKT2*(HR-CPA*TMELT))
   42 PXE=11.05E+04/TMELT
      TMDOT=DMD*(1.+2.64E+09/(PBL**.67*E**PXE))
      CDOT=TMDOT/RHOV
   43 SDOT(LEN)=SDOT(LEN)+CDOT*DELT
      JIND(LEN)=1
      DO 44 N=1,NAL
      BN=N
      IF (BN*DEL(1,1)-SDOT(LEN)) 44,44,45
   44 CONTINUE
      PRINT 84
      GO TO 69
   45 DE(N,LEN)=DEL(N,LEN)-(SDOT(LEN)-(BN-1.)*DEL(1,LEN))
      PCM=VCP(N,LEN)*VRHO(N,LEN)*DE(N,LEN)**2/(DELT*VTC(N,LEN))
      IF (PCM-2.) 46,47,47
   46 DE(N,LEN)=0.
      CN=N
      SDOT(LEN)=CN*TOL
```

```
      IND(N+1,LEN)=1
47    IND(N,LEN)=1
      WT(LEN)=PI*(RL(LEN)+RS(LEN)-2.*SDOT(LEN))*CDOT*RHOC*SOL(LEN)
      IF (N.EQ.1) GO TO 48
      DE(N-1,LEN)=0.
48    K=K+1
      IF (K.LE.NAL) GO TO 28
      TW(K,LEN)=TW(K,LEN)+DELT*(VTC(K-1,LEN)/(VRHO(K-1,LEN)*VCP(K-1,LEN)
     1*DE(K-1,LEN)**2)*(TW(K-1,LEN)-TW(K,LEN))-VTC(K,LEN)/(VRHO(K,LEN)*V
     2CP(K,LEN)*DEL(K,LEN)**2)*(TW(K,LEN)-TW(K+1,LEN)))
      IF (TW(K,LEN).GT.1060.) TW(K,LEN)=1060.
      K=K+1
      TW(K,LEN)=TW(K,LEN)+DELT*(VTC(K-1,LEN)/(VRHO(K-1,LEN)*VCP(K-1,LEN)
     1*DEL(K-1,LEN)**2)*(TW(K-1,LEN)-TW(K,LEN)))
      IF (TW(K,LEN).GT.860.) TW(K,LEN)=860.
      NAL=NALI
49    CONTINUE
C     ******************************************************************
      LEN=NOFXP
      DO 50 N=1,NALS
      AN=N
      IF (AN*DEL(1,NOFXP)-SDOT(LEN)) 50,50,51
50    CONTINUE
      PRINT 85
      GO TO 69
51    KS=N
      TMELT=6400.
      STR=TEMP+.58*(TW(KS,LEN)-TEMP)+.19*(STAW-TEMP)
      CALL TCAT (STCA,STR)
      CALL VISCOT (SVISG,STR)
      IF (JIND(LEN).EQ.0) GO TO 52
C     ****************************************************************
      CALL GCPB (GCP,P)
      IF (LEN.GE.NOFX) GCP=.4
C     ****************************************************************
      CALL GASTC (GTC,GCP)
      SPR=GCP*GVIS/GTC
      GO TO 53
52    SPR=CPA*SVISG/STCA
53    SRF=SPR**.5
      CALL PRESS(PRE,ALT)
      PTS=PRE*((1.[illegible]*AMACH**2)**3.5)*((6.0/(7.0*AMACH**2-1.0))**2.5)
      RHOWS=PTS [illegible]*STR)
      DV=1./SN[illegible](2.*(PTS-PRE)/RHOWS)
      GTAB=((1.[illegible]5.0/(AMACH**2))*(1.0-1.0/(1.4*AMACH**2)))**0.25
      SQDOTC=0.[illegible]3*GTAB*SQRT(RHOWS*SVISG*DV*G [illegible])*(V**2)/(2.*G*AJ)
55    SDTR=V**2/(2.*G*AJ*CPA)
      STAW=TEMP+SRF*SDTR
      STG=TEMP+SDTR
      STREC=TEMP+SRF*(STG-TEMP)
      SHE=SQDOTC/(STG-TW(KS,LEN))
56    IF (IND(KS,LEN).EQ.1) GO TO 57
      IF (TW(KS,LEN).GE.TMELT) GO TO 57
      STWK=TW(KS,LEN)
      CALL TCATJ (SVT,STWK)
      CALL CPATJ (SVC,STWK)
      SARHO(KS)=ATJRHO
      SATC(KS)=SVT
      SACP(KS)=SVC
      IF (KS.EQ.1) GO TO 58
      TW(KS,LEN)=TW(KS,LEN)+DELT*(SATC(KS-1)/(SARHO(KS-1)*SACP(KS-1)*DE(
     1KS-1,LEN)**2)*(TW(KS-1,LEN)-TW(KS,LEN))-SATC(KS)/(SARHO(KS)*SACP(K
```

```
     2S)*DE(KS,LEN)**2)*(TW(KS,LEN)-TW(KS+1,LEN)))
      IF (TW(KS,LEN).LE.TMELT) GO TO 65
      TW(KS,LEN)=TMELT-1.
      GO TO 65
 57   STWK=TW(KS,LEN)
      CALL TCATJ (SCT,STWK)
      CALL CPATJ (SCC,STWK)
      SARHO(KS)=ATJRHO
      SATC(KS)=SCT
      SACP(KS)=SCC
      IND(KS,LEN)=1
 58   TW(KS,LEN)=TW(KS,LEN)+DELT/(SACP(KS)*SARHO(KS)*DE(KS,LEN))*(SHE*(S
     1TG -TW(KS,LEN))-SATC(KS)/DE(KS,LEN)*(TW(KS,LEN)-TW(KS+1,LEN)))*2.
      IF (TW(KS,LEN).GE.TMELT) GO TO 59
      JIND(LEN)=0
      GO TO 65
 59   TW(KS,LEN)=TMELT
      HR=CPA*TEMP+RF*V**2/(2.*G*AJ)
      SQCOND=-SATC(KS)*(TW(KS,LEN)-TW(KS+1,LEN))/DE(KS,LEN)
      SQTOT=SQDOTC+SQCOND
      IF (SQTOT.LE.0.0) GO TO 65
      IND(KS,LEN)=1
      JIND(LEN)=1
      DELH=HR-CPA*TMELT
      QSTARS=2000.+2.*DELH
      CDOTS=SQTOT/(QSTARS*ATJRHO)
      SDOT(LEN)=SDOT(LEN)+CDOTS*DELT
      SS=CDOTS
      RX=RX+1./(1.-SIN(THETC))*(SIN(THETC)*SS-CDOT)
      SX=.01745*RX*PHI
      IF (SX.LE.0.0) SX=.01943
      IF (RX.LE.0.0) RX=.01387
      SNR=RX
      DO 60 N=1,NALS
      BN=N
      IF (BN*DEL(1,NOFXP)-SDOT(LEN)) 60,60,61
 60   CONTINUE
      PRINT 86
      GO TO 69
 61   DE(N,LEN)=DEL(N,LEN)-(SDOT(LEN)-(BN-1.)*DEL(1,NOFXP))
      PCM=SACP(N)*SARHO(N)*DE(N,LEN)**2/(DELT*SATC(N))
      IF (PCM-2.) 62,63,63
 62   DE(N,LEN)=0.
      SDOT(LEN)=BN*STOL
      IND(N,LEN)=1
      IND(N+1,LEN)=1
 63   IF (N.EQ.1) GO TO 65
      NM=N-1
      DO 64 I=1,NM
 64   DE(I,LEN)=0.
 65   KS=KS+1
      IF (KS.LE.NALS) GO TO 56
      TW(KS,LEN)=TW(KS,LEN)+DELT*(SATC(KS-1)/(SARHO(KS-1)*SACP(KS-1)*DE(
     1KS-1,LEN)**2)*(TW(KS-1,LEN)-TW(KS,LEN))-SATC(KS)/(SARHO(KS)*SACP(K
     2S)*DE(KS,LEN)**2)*(TW(KS,LEN)-TW(KS+1,LEN)))
      IF (TW(KS,LEN).GT.1060.) TW(KS,LEN)=1060.
      KS=KS+1
      TW(KS,LEN)=TW(KS,LEN)+DELT*(SATC(KS-1)/(SARHO(KS-1)*SACP(KS-1)*DE(
     1KS-1,LEN)**2)*(TW(KS-1,LEN)-TW(KS,LEN)))
      IF (TW(KS,LEN).GT.860.) TW(KS,LEN)=860.
C     ******************************************************************
      TMELT=6760.
```

```
C      ***************************************************************
       TOTWT=0.
       WDOT=0.0
       DO 66 LL=1,NOFX
       TOTWT=TOTWT+PI*(RS(LL)+RL(LL)-SDOT(LL))*SDOT(LL)*RHOV*SOL(LL)
66     WDOT=WDOT+WT(LL)
       SWTL=.0698*PHI*SNRI**2*SDOT(NOFXP)*ATJRHO
       WT(NOFXP)=2.*PI*SNR**2*CDOTS*ATJRHO
       TOTWT=TOTWT+SWTL
       WDOT=WDOT+WT(NOFXP)
       VMAS=BI-TOTWT/G
       RAD=RADI-SDOT(NOFXM)
       ALGTH=ALGTHI-SDOT(NOFXP)
       AREA=PI*RAD**2
       SLANT=ALGTH/(COS(THETC)-SNR/RAD*(1.-SIN(THETC)))
       ATL=AT-DELT/6.
       ATH=AT+DELT/6.
       IF (ALT.LE.0.0) GO TO 68
       IF (T.GT.ATL.AND.T.LT.ATH) GO TO 67
       GO TO 8
67     IF (LLL.LT.8) GO TO 68
       LLL=0
       PRINT 80
68     PRINT 81, T,X,Y,Z,ALT,GAMMA,VMAS,PSI,V,QD,AMACH,CD,ANR,PHI,THE,ALP
      1,BET,PS,ALPT,XE,YE,ZE,FD,FN,GFZ,CLAT,DLON,ABETA,GCIR,AIZ,AIX
       PRINT 82, CP,CAN,CPB,CDF,ANRE
       PRINT 83, RHO,VIS,AMACHE,TEMPE,RHOE,VE,VISG,PBE
       LLL=LLL+1
       AT=AT+1.0
       PRINT 87, (SDOT(I),I=1,NOFXP)
       PRINT 70, ((TW(I,J),J=1,NOFX),I=1,NP2)
       PRINT 86, TW(NALC1,NOFX),TW(NALC2,NOFX)
       PRINT 89, WDOT,TOTWT,RX
       PRINT 90, QSTAR
       PRINT 91, (TW(I,NOFXP),I=1,NP2S)
       IF (ALT) 69,69,8
69     CONTINUE
C
C
70     FORMAT (30X,8F8.0)
71     FORMAT (1H1)
72     FORMAT (*JIND*10I4)
73     FORMAT (*IND*8I4/(10X,8I4))
74     FORMAT (*VCF*8E12.3/(11X,8E12.3))
75     FORMAT (*VTC*8E12.3/(11X,8E12.3))
76     FORMAT (*VRHO*8E12.3/(11X,8E12.3))
77     FORMAT (*DEL*8E12.3/(11X,8E12.3))
78     FORMAT (*DE*8E12.3/(11X,8E12.3))
79     FORMAT (*TW*8E12.3/(11X,8E12.3))
80     FORMAT (12X,4HTIME,14X,1HX,18X,1HY,15X,1HZ,16X,3HALT,13X,5HGAMMA,1
      11X,4HVMAS/30X,4HPSI,15X,3HVEL,13X,2HQD,15X,5HAMACH,11X,2HCD,14X,3H
      2REN/30X,3HPHI,16X,5HTHETA,11X,5HALPHA,12X,3HBET,13X,2HPS,14X,4HALP
      3T/30X,2HXE,17X,2HYE,14X,2HZE,15X,2HFD,14X,2HFN,14X,3HGFZ/30X,3HLAT
      4,16X,4HLONG,12X,4HBETA,13X,4HGCIR,12X,2HIZ,14X,2HIX)
81     FORMAT (1H0,4X,7E17.7/(22X,6E17.7))
82     FORMAT (10X,5E10.3)
83     FORMAT (5X,8E10.3)
84     FORMAT (10H  OVERHEAT/)
85     FORMAT (*OVERHEATSTAG1*/)
86     FORMAT (*OVERHEATSTAG2*/)
87     FORMAT (10X*SDOT*9E12.3)
88     FORMAT (86X,F8.0)
```

```
89    FORMAT (10X*WTLOSSRATEIS*E11.4*LBS/SECANDTOTALWTLOSSIS*E13.4*LBSAN
     1DNOSERADIS*E11.4*FT*)
90    FORMAT (10X*QSTARIS*E11.4*BTU/LB*)
91    FORMAT (30X,13F8.0)
92    FORMAT(*    SDOT*  10F8.5)
      END
```

```
      SUBROUTINE ATTK (VRZ4,VRY4,ALP,PI)
C     COMPUTES ANGLE OF ATTACK,ALP.
      IF (VRZ4) 9,5,1
1     IF (VRY4) 4,3,2
2     ALP=ATAN(VRY4/VRZ4)
      RETURN
3     ALP=0.
      RETURN
4     ALP=ATAN(VRY4/VRZ4)
      RETURN
5     IF (VRY4) 6,7,8
6     ALP=-PI/2.
      RETURN
7     ALP=0.
      RETURN
8     ALP=PI/2.
      RETURN
9     IF (VRY4) 10,11,12
10    ALP=-PI+ATAN(VRY4/VRZ4)
      RETURN
11    ALP=PI
      RETURN
12    ALP=PI+ATAN(VRY4/VRZ4)
      RETURN
      END
```

```
      SUBROUTINE CDSF (CD,AM,ANR)
C     COMPUTES INVISCID DRAG
      COMMON /B/ AREA,RAD,SLANT,SNR,THETC,V
      COMMON /C/ CPM,CP,CAN,CPB,CDF
      PI=3.14159
      G=32.174
      ANOSE=PI*(SNR**2)
      WAREA=PI*RAD*SLANT
      AMACH=AM
      PR=.89
      CPM=1.42857/(AM**2)*((6.*(AM**2)/5.)**3.5*(6./(7.*(AM**2)-1.))**2.
     15-1.)
      CP=4.*(SIN(THETC))**2*(2.5+8.*AMACH*SIN(THETC))/(1.+16.*AMACH*SIN(
     1THETC))
      CAN=(.55-CP)*ANOSE/AREA
      CPB=1.001/AM**2
      CALL CDFM (CDF)
      CD=CP+CAN+CPB+CDF
      RETURN
      END
```

```
      SUBROUTINE LONG (DLG,XE,YE,PI)
C     THIS SUB COMPUTES LONGITUDE
      IF (YE) 1,6,4
1     IF (XE) 2,9,3
2     DLG=-PI+ATAN(YE/XE)
      RETURN
3     DLG=ATAN(YE/XE)
      RETURN
4     IF (XE) 5,10,3
5     DLG=PI+ATAN(YE/XE)
      RETURN
6     IF (XE) 7,7,8
7     DLG=PI
      RETURN
8     DLG=0.0
      RETURN
9     DLG=-PI/2.
      RETURN
10    DLG=PI/2.
      RETURN
      END
```

```
      SUBROUTINE INITIAL (SNR,THETC,SLANT)
C
C      THIS SUBROUTINE PROVIDES THE NECESSARY GEOMETRY CALCULATIONS AND
C     CHANGES IN UNITS FOR PROGRAM STRAB6
C
      COMMON /D/ TW(50,12),IND(50,12),JIND(12),VCP(50,12),VTC(50,12),VRH
     1O(50,12),DEL(50,12),DE(50,12),SDOT(12),XI(12),RS(12),RL(12),SOL(12
     2),WT(12),TM(12),TWT(12),SACP(50),SATC(50),SARHO(50),RN(12)
      COMMON /F/ NOFX,ALGTH,RADI,POS(11),AZN,GLAT
      AZN=AZN/57.296
      GLAT=GLAT/57.296
      ALGTH=POS(NOFX)/12.
      IM=NOFX-1
      STH=SIN(THETC)
      CTH=COS(THETC)
      DO 1 I=1,IM
      RN(I)=6.6E+07
      SOL(I)=(POS(I+1)-POS(I))/(12.0*CTH)
    1 RS(I)=SNR*CTH+(POS(I)/12.0-SNR*(1.0-STH))*STH/CTH
      RN(NOFX)=5.0E+06
      RN(NOFX+1)=1.5E+06
      RS(NOFX)=SNR
      RS(NOFX+1)=SNR
      SOL(NOFX)=(POS(1)/12.0-SNR*(1.0-STH))/CTH
      RADI=SNR*CTH+(ALGTH-SNR*(1.0-STH))*STH/CTH
      IM=NOFX-2
      DO 2 I=1,IM
    2 RL(I)=RS(I+1)
      RL(NOFX-1)=RADI
      RL(NOFX)=RS(1)
      SLANT=0.0
      DO 3 I=1,NOFX
    3 SLANT=SLANT+SOL(I)
      RETURN
      END
```

```
      SUBROUTINE CDFM (CDF)
C     THIS SUB COMPUTES SKIN FRICTION DRAG
      COMMON /B/ AREA,RAD,SLANT,SNR,THETC,V
      COMMON /D/ TW(50,12),IND(50,12),JIND(12),VCP(50,12),VTC(50,12),VRH
     10(50,12),DEL(50,12),DE(50,12),SDOT(12),XI(12),RS(12),RL(12),SOL(12
     2),WT(12),TM(12),TWT(12),SACP(50),SATC(50),SARHO(50),RN(12)
      COMMON /E/ NOFXM,NAL,ALT,AMACH,QD,AMACHE,TEMPE,RHOE,VE,VISG,PBE,AN
     1RE
      TWA=0.
      CDF=0.0
      SR=SNR/RAD
      PI=3.14159
      CALL RHOF (RHO,ALT)
      CALL VISCO (VIS,ALT)
      CALL VSD (VS,ALT)
      CALL PRESS (PRE,ALT)
      CALL TEMPA (TEMP,ALT)
      AMACH=V/VS
      TEMPE=TEMP*(1.+.0966*AMACH*SIN(THETC)+.2267*(AMACH*SIN(THETC))**2)
      VE=V*(1.-1.4/AMACH**2*(AMACH*SIN(THETC))**1.9)**.5
      AMACHE=AMACH*(VE/V)*(TEMP/TEMPE)**.5
      R1=1716.
      AM=AMACH
      AM=AMACH
      PBE=PRE*(1.+2.8*AM**2*(SIN(THETC))**2*(2.5+8.*AM*SIN(THETC))/(1.+1
     16.*AM*SIN(THETC)))
      RHOE=PBE/(R1*TEMPE)
      CALL VISCOT (VISG,TEMPE)
      AREA=PI*RAD**2
      ANRE=RHOE*VE*SLANT*32.174/VISG
      COTT=1./TAN(THETC)
      DO 2 K=1,NOFXM
      DO 1 M=1,NAL
      IF (DE(M,K).LE.0.) GO TO 1
      TWA=TWA+TW(M,K)/8.
    1 CONTINUE
    2 CONTINUE
      RE=RHO*V*SLANT/VIS
      IF (ANRE-2.0E+07) 3,4,4
    3 HSH=.5+.5*(TWA/TEMPE)+.0374*(AMACHE)**2
      CDF1=(1.53/RE**.5)*(VE/V)**1.5*(PBE/PRE)**.5*(TEMP/TEMPE)**.185*(1
     1./HSH)**.185*COTT
      CDF=CDF1*((1.+9.8842*SR-44.0235*SR**2+70.383*SR**3)-(SR**(.69+2.1*
     1SR)*ALOG10(RE)))
      GO TO 5
    4 HSH=.5+.5*(TWA/TEMPE)+.0388*(AMACHE)**2
      CDF1=(.0776/RE**.2)*(VE/V)**1.8*(PBE/PRE)**.8*(TEMP/TEMPE)**.58*(1
     1./HSH)**.58*COTT
      CDF=CDF1*(1.-((.8+.052*AMACH)*SR))
    5 CDF=CDF
      RETURN
      END
```

```
      SUBROUTINE VISCOT (VISG,TEMP)
C     THIS SUB COMPUTES VISCOSITY OF AIR VS TEMP
C     UNITS ARE LB/FT-SEC
      IF (TEMP-2460.) 2,1,1
1     VISG=41.0E-10*TEMP+2.4414E-05
      RETURN
2     IF (TEMP-1160.) 4,3,3
3     VISG=100.769E-10*TEMP+.97108E-05
      RETURN
4     IF (TEMP-760.) 6,5,5
5     VISG=132.5E-10*TEMP+.603E-05
      RETURN
6     VISG=166.666E-10*TEMP+.34334E-05
      RETURN
      END
```

```
      SUBROUTINE PRESS (PE,ALT)
C     COMPUTES PRESSURE PER ALTITUDE
C     LBS/FT2
      PE=2116.2*EXP(-4.25509E-05*ALT)
      RETURN
      END
```

```
      SUBROUTINE VSD (VS,ALT)
C     THIS SUB COMPUTES SPEED OF SOUND
C     UNITS ARE FT/SEC
      IF (ALT-36000.) 1,1,2
1     VS=1116.9-.412E-02*ALT
      RETURN
2     IF (ALT-82000.) 3,3,4
3     VS=968.5
      RETURN
4     IF (ALT-154000.) 5,5,6
5     VS=814.+.191E-02*ALT
      RETURN
6     IF (ALT-172000.) 7,7,8
7     VS=1106.
      RETURN
8     IF (ALT-262000.) 9,9,10
9     VS=1527.-.245E-02*ALT
      RETURN
10    VS=846.
      RETURN
      END
```

```
      SUBROUTINE GCPB (GCP,PBL)
C     THIS SUB COMPUTES ABLATIVE GAS SPECIFIC HEAT
C     UNITS ARE BTU/LB-DEG R
      IF (PBL-10.) 2,1,1
1     GCP=-.228*ALOG(PBL)+3.22
      RETURN
2     IF (PBL-.009) 4,3,3
3     GCP=-.30882*ALOG(PBL)+3.4
      RETURN
4     IF (PBL-.0001) 6,5,5
5     GCP=.7374*ALOG(PBL)+8.37
      RETURN
6     IF (PBL-1.0E-05) 8,7,7
7     GCP=.12333*ALOG(PBL)+2.709
      RETURN
8     GCP=1.284
      RETURN
      END
```

```
      SUBROUTINE TEMPA (TEMP,ALT)
C     THIS SUB COMPUTES TEMP OF AIR VS ALT     TO 300,000
C     TEMP IS IN DEGREES RANKINE
      IF (ALT-261000.) 2,1,1
1     TEMP=298.2
      RETURN
2     IF (ALT-175500.) 4,3,3
3     TEMP=-2.463E-03*ALT+941.04
      RETURN
4     IF (ALT-154000.) 6,5,5
5     TEMP=508.79
      RETURN
6     IF (ALT-85000.) 8,7,7
7     TEMP=1.627E-03*ALT+256.05
      RETURN
8     IF (ALT-35700.) 10,9,9
9     TEMP=389.99
      RETURN
10    TEMP=-36.77E-04*ALT+518.7
      RETURN
      END
```

```
      SUBROUTINE TCAT (TCA,TEMP)
C     THIS SUB COMPUTES THERMAL COND. OF AIR VS. TEMP
C     UNITS ARE BTU/SEC-FT-DEGREE RANKINE
      IF (TEMP-2960.) 2,1,1
1     TCA=6.0E-06*TEMP+.03324
      GO TO 9
2     IF (TEMP-2460.) 4,3,3
3     TCA=7.8E-06*TEMP+.028
      GO TO 9
4     IF (TEMP-1960.) 6,5,5
5     TCA=14.2E-06*TEMP+.01217
      GO TO 9
6     IF (TEMP-1160.) 8,7,7
7     TCA=16.5E-06*TEMP+.00766
      GO TO 9
8     TCA=19.28E-06*TEMP+.00444
9     TCA=TCA/3600.
      RETURN
      END
```

```
      SUBROUTINE VCPFC (VCP,TEMP)
C     THIS SUB COMPUTES VIRGIN SPECIFIC HEAT VS. TEMP
C     UNITS ARE BTU/LB-DEG R
      IF (TEMP-4000.) 2,1,1
1     VCP=.55E-04*TEMP+1.23
      RETURN
2     IF (TEMP-2000.) 4,3,3
3     VCP=.19E-03*TEMP+.69
      RETURN
4     IF (TEMP-1060.) 6,5,5
5     VCP=.556E-03*TEMP-.0423
      RETURN
6     IF (TEMP-860.) 8,7,7
7     VCP=.975E-03*TEMP-.4865
      RETURN
8     IF (TEMP-660.) 10,9,9
9     VCP=.21E-03*TEMP+.1714
      RETURN
10    VCP=.375E-03*TEMP+.0625
      RETURN
      END
```

```
      SUBROUTINE RHOF (RHO,ALT)
C     THIS SUB COMPUTES DENSITY OF AIR VS. ALTITUDE
      COMMON /A/ RE
      GALT=RE*ALT/(RE+ALT)
      RHO0=.0023769
      R=53.352
      E=2.7183
      IF (GALT-36089.) 1,1,2
1     T=518.688-3.56616*GALT/1000.
      RHO=RHO0*(T/518.668)**4.256
      RETURN
2     IF (GALT-82021.) 3,3,4
3     EP2=(36089.-GALT)/(R*389.988)
      RHO=RHO0*.297069*E**EP2
      RETURN
4     IF (GALT-154199.) 5,5,6
5     T=254.988+1.64592*GALT/1000.
      RHO=RHO0*.0326657*(T/389.988)**-12.388
      RETURN
6     IF (GALT-173885.) 7,7,8
7     EP4=(154199.-GALT)/(R*508.788)
      RHO=RHO0*.00121179*E**EP4
      RETURN
8     IF (GALT-259186.) 9,9,10
9     T=938.088-2.46888*GALT/1000.
      RHO=RHO0*5.86784E-04*(T/508.788)**6.592
      RETURN
10    IF (GALT-295276.) 11,11,12
11    EP6=(259186.-GALT)/(R*298.186)
      RHO=RHO0*1.73274E-05*E**EP6
      RETURN
12    T=-349.812+2.19456*GALT/1000.
      RHO=RHO0*1.792653E-06*(T/298.188)**-9.541
      RETURN
      END
```

```
      SUBROUTINE VISCO (VIS,ALT)
C     THIS SUB COMPUTES VISCOSITY OF AIR VS. ALTITUDE
C     UNITS ARE IN LB-SEC/FT**2
      IF (ALT-270000.) 2,1,1
1     VIS=2.35E-07
      RETURN
2     IF (ALT-175500.) 4,3,3
3     VIS=-1.509E-12*ALT+6.333E-07
      RETURN
4     IF (ALT-156000.) 6,5,5
5     VIS=3.68E-07
      RETURN
6     IF (ALT-83250.) 8,7,7
7     VIS=.973E-12*ALT+2.172E-07
      RETURN
8     IF (ALT-34500.) 10,9,9
9     VIS=2.969E-07
      RETURN
10    VIS=-2.124E-12*ALT+3.737E-07
      RETURN
      END
```

```
      SUBROUTINE CCPP (CCP,TEMP)
C     THIS SUB COMPUTES CHAR SPECIFIC HEAT VS. TEMP
C     UNITS ARE BTU/LB-DEG R
      IF (TEMP-6000.) 2,1,1
1     CCP=.4
      RETURN
2     IF (TEMP-4000.) 4,3,3
3     CCP=.125E-04*TEMP+.3215
      RETURN
4     IF (TEMP-3000.) 6,5,5
5     CCP=.305E-04*TEMP+.2495
      RETURN
6     IF (TEMP-2000.) 8,7,7
7     CCP=.67E-04*TEMP+.14
      RETURN
8     IF (TEMP-1060.) 10,9,9
9     CCP=.207E-03*TEMP-.14
      RETURN
10    CCP=.96E-04*TEMP-.02236
      RETURN
      END
```

```
      SUBROUTINE SSLP (VRZ4,VRX4,BET,PI)
C     COMPUTES ANGLE OF SIDESLIP
      IF (VRZ4) 9,5,1
1     IF (VRX4) 4,3,2
2     BET=ATAN(VRX4/VRZ4)
      RETURN
3     BET=0.
      RETURN
4     BET=ATAN(VRX4/VRZ4)
      RETURN
5     IF (VRX4) 6,7,8
6     BET=-PI/2.
      RETURN
7     BET=0.
      RETURN
8     BET=PI/2.
      RETURN
9     IF (VRX4) 10,11,12
10    BET=-PI+ATAN(VRX4/VRZ4)
      RETURN
11    BET=PI
      RETURN
12    BET=PI+ATAN(VRX4/VRZ4)
      RETURN
      END
```

```
      SUBROUTINE VTCPC (VTC,TEMP)
C     UNITS ARE BTU/FT-SEC-DEG R
      IF (TEMP-4000.) 2,1,1
1     VTC=.705E-07*TEMP+.58E-04
      RETURN
2     IF (TEMP-2000.) 4,3,3
3     VTC=.695E-07*TEMP+.62E-04
      RETURN
4     VTC=.7376E-07*TEMP+.5347E-04
      RETURN
      END
```

```
      SUBROUTINE ACMQ (C,A)
C     COMPUTES DAMPING COEFFICIENT
      IF (A.GT.17.) GO TO 1
      IF (A.GT.9.) GO TO 2
      IF (A.GT.7.) GO TO 3
      IF (A.GT.5.) GO TO 4
      IF (A.GT.4.) GO TO 5
      IF (A.GT.3.) GO TO 6
      C=2.5*A-10.
      RETURN
1     C=-2.4
      RETURN
2     C=.05*A-3.25
      RETURN
3     C=.1*A-3.7
      RETURN
4     C=.3*A-5.3
      RETURN
5     C=.7*A-7.3
      RETURN
6     C=A-8.5
      RETURN
      END
```

```
      SUBROUTINE GASTC (GTC,GCP)
C     COMPUTES ABLATIVE GAS THERMAL
C     CONDUCTIVITY.  BTU/SEC-FT-DEG.R.
      GTC=4.429E-05*(GCP+.297)
      RETURN
      END
```

```
      SUBROUTINE ACNA (C,A)
C     COMPUTES NORMAL FORCE COEFF.
C     CNA PER DEGREE
      C=.034
      RETURN
      END
```

```
      SUBROUTINE CTCPC (CTC,TEMP)
C     THIS SUB COMPUTES CHAR THERMAL CONDUCTIVITY VS. TEMP
C     UNITS ARE BTU/FT-SEC-DEG R
      IF (TEMP-6000.) 1,2,2
      CTC=.56E-07*TEMP+.053E-03
      RETURN
2     CTC=.389E-03
      RETURN
      END
```

```
      SUBROUTINE CPATJ (S,T)
C     COMPUTES SPEC HEAT OF ATJ GRAPHITE VS. TEMP
C     UNITS   BTU/LB-DEG-R
      IF (T-2000.) 1,2,2
1     IF (T-1000.) 4,3,3
2     S=3.482E-05*T+.35536
      RETURN
3     S=1.25E-04*T+.175
      RETURN
4     S=3.409E-04*T-.0409
      RETURN
      END
```

```
      SUBROUTINE TCATJ (C,T)
C     COMPUTES THER. COND. OF ATJ GRAPHITE VS. TEMP
      IF (T-3460.) 1,3,3
1     IF (T-2460.) 2,4,4
2     IF (T-1460.) 6,5,5
3     C=(2.E-05*T+.2808)/60.
      RETURN
4     C=.35/60.
      RETURN
5     C=(-1.84E-04*T+.80264)/60.
      RETURN
6     C=(-3.82E-04*T+1.091)/60.
      RETURN
      END
```

APPENDIX II

STRAB-6 PROGRAM LISTING FOR MULTIPLE CASE RUN

```
WJM62,6,2500,65000.MOULDS,627A,WODE.
RUNJ(S,40000,,,,,77000)
RFL(40000)
STRAB62.
         PROGRAM STRAB62 (INPUT,OUTPUT)
C        6 DEGREE TRAJECTORY WITH ABLATION HEATING AND STAG                 A   2
         COMMON /A/ RE                                                      A   3
         COMMON /B/ AREA,RAD,SLANT,SNR,THETC,V                              A   4
         COMMON /C/ CPM,CP,CAN,CPB,CDF                                      A   5
         COMMON /D/ TW(50,12),IND(50,12),JIND(12),VCP(50,12)VTC(50,12),VRH  A   6
        10(50,12),DEL(50,12),DE(50,12)SDOT(12),XI(12),RS(12),RL(12),SOL(12  A   7
        2),WT(12),TM(12),TWT(12),SACP(50),SATC(50),SARHO(50),RN(12),QSTR(12 A   8
        3),QDOTC(12),QTOT(12),QCOND(12)                                     A   9
         COMMON /E/ NOFXM,NAL,ALT,AMACH,QD,AMACHE,TEMPE,RHOE,VE,VISG,PBE,AN A  10
        1RE                                                                 A  11
         COMMON /F/ NOFX,ALGTH,RADI,POS(11),AZN,GLAT                        A  12
C        VEHICLE DATA                                                       A  13
C        IF NOFX IS CHANGED CHANGE FORMAT 103                               A  14
C        IF CONE ANGLE IS CHANGED SUB CDSF MUST BE CHANGED                  A  15
700      1500 READ 1500,NCASE,(POS(J),J=1,8)
         FORMAT(I2,7A10,A8)
         PRINT 1501,NCASE,(POS(J),J=1,8)
         1501 FORMAT(1H1,30X,7A10,A8)
         ETC.
```

```
      DATA SNR,THETC,BI,SM/.0208,.07853,6.27836,.59718/*                   A  15
      DATA PI,E,AJ,GRAV,G/3.14159,2.7183,778.,32.174,32.174/               A  17
      DATA REQ,PE,ET,WE/20.927491E+06,.673852E-02,.08181333,0.7292E-04/    A  18
      DATA NOFX,NAL,NALC,NALS/8,4,10,35/*                                  A  19
      DATA DELT,DT,H,BT,AT/.05,.0005,.001,.05,1./                          A  20
      DATA AZN,CLAT,DLON,GAMMA/154.,33.996,-107.5,-22.39/*                 A  21
      DATA V,Z,ALPHA/15167.,2.50E+05,7./*                                  A  22
      DATA (POS(I),I=1,8)/6.607,18.570,30.533,42.496,54.459,66.422,78.38*  A  23
      AREA=PI*RAD**2                                                       A 757
      SLANT=ALGTH/(COS(THETC)-SNR/RAD*(1.-SIN(THETC)))                     A 758
      ATL=AT-DELT/6.                                                       A 759
      ATH=AT+DELT/6.                                                       A 760
      IF (ALT.LE.0.0) GO TO 68                                             A 761
      IF (T.GT.ATL.AND.T.LT.ATH) GO TO 67                                  A 762
      GO TO 8                                                              A 763
   67 IF (LLL.LT.8) GO TO 68                                               A 764
      LLL=0                                                                A 765
      PRINT 80                                                             A 766
   68 PRINT 81, T,X,Y,Z,ALT,GAMMA,VMAS,PSI,V,QD,AMACH,CD,ANR,PHI,THE,ALP   A 767
     1,BET,PS,ALPT,XE,YE,ZE,FD,FN,GFZ,CLAT,DLON,ABETA,GCIR,AIZ,AIX         A 768
      PRINT 82, CP,CAN,CPB,CDF,ANRE                                        A 769
      PRINT 83, RHO,VIS,AMACHE,TEMPE,RHOE,VE,VISG,PBE                      A 770
      LLL=LLL+1                                                            A 771
      AT=AT+1.0                                                            A 772
```

*These data cards can be removed and read into program by multi-case read statements.

```
      PRINT 87, (SDOT(I),I=1,NOFXP)                                 A 773
      PRINT 70, ((TW(I,J),J=1,NOFX),I=1,NP2)                        A 774
      PRINT 88, TW(NALC1,NOFX),TW(NALC2,NOFX)                       A 775
      PRINT 89, WDOT,TOTWT,RX                                       A 776
      PRINT 90, QSTAR                                               A 777
      PRINT 91, (TW(I,NOFXP),I=1,NP2S)                              A 778
      IF (ALT) 69,69,8                                              A 779
69    IF (NCASE.NE.0) GO TO 700                                     A 780
C                                                                   A 781
C                                                                   A 782
70    FORMAT (30X,8F8.0)                                            A 783
71    FORMAT (1H1)                                                  A 784
```

APPENDIX III

SAMPLE CASE OUTPUT

```
TIME            X               Y               Z               ALT             GAMMA           VMAS
                PSI.            VEL             QD              AMACH           CD              REN
                PHI             THETA           ALPHA           BET             PS              ALPT
                XF              YE              ZE              FD              FN              GFZ
                LAT             LONG            BETA            GCIR            IZ              IX

0.              0.              0.              2.5000000E+05   2.5000000E+05   -2.2390000E+01  6.2783600E+00
                0.              1.5167000E+04   8.9088100E+00   1.6585019E+01   1.3942240E-01   3.3674106E+04
                1.8394009E+00   0.              0.              0.              0.              7.00[illegible]00E+00
                0.              0.              0.              0.              0.              0.
                3.3817746E+01   -1.0750000E+02  0.              0.              5.1000000E-01   2.3080000E+01

1.0000000E+00   2.3702650E-01   1.4023633E+04   2.4420767E+05   2.4421349E+05   -2.2495287E+01  6.2783600E+00
                1.9322043E-03   1.5178582E+04   1.1740936E+01   1.6344308E+01   1.5221524E-01   4.3663176E+04
                1.0717959E+02   -7.9831134E-02  5.3157835E+00   8.1503590E-02   6.2831627E+00   5.3157835E+00
                1.7578217E+07   6.1474736E+03   1.1761207E+07   1.9297126E+00   2.2912934E+00   -3.0491921E-01
                3.3785656E+01   -1.0747998E+02  1.2290268E+03   1.5223763E+04   5.1000000E-01   2.3080000E+01
     1.460E-02 6.739E-04 3.747E-03 1.034E-01 8.481E+04
1.019E-07 2.648E-07 1.330E+01 5.081E+02 2.777E-07 1.511E+04 3.835E-05 2.422E-01
  SDOT    0.        0.        0.        0.        0.        0.        0.        0.        0.
                     610   593   584   579   575   573   571   593
                     546   545   545   545   545   545   545   585
                     544   544   544   544   544   544   544   578
                     544   544   544   544   544   544   544   572
                     544   544   544   544   544   544   544   567
                     544   544   544   544   544   544   544   563
                                                             554
                                                             545
WTLOSSRATEIS 0.     LBS/SECANDTOTALWTLOSSIS     0.     LBSANDNOSERADIS 2.0800E-02FT
QSTARIS 0.        BTU/LB
                     710   676   649   629   612   599   588   579   572   567   562   559   556
                     553   551   550   548   547   547   546   546   545   545   545   545   544
                     544   544   544   544   544   544   544   544   544   544   544

2.0000000E+00   9.3834264E-01   2.8047303E+04   2.3838509E+05   2.3840486E+05   -2.2601020E+01  6.2783600E+00
                3.7681252E-03   1.5190215E+04   1.5321872E+01   1.6109963E+01   1.1221135E-01   5.5112214E+04
                1.1207642E+02   -5.5755317E-01  5.2495952E-01   5.6078651E-01   1.2565903E+01   5.2495952E-01
                1.7580437E+07   1.2294546E+04   1.1747501E+07   1.8564377E+00   2.9528972E-01   -3.8503174E-01
                3.3751438E+01   -1.0745993E+02  1.6671809E+03   3.1459681E+04   5.1000000E-01   2.3080000E+01
     1.467E-02 6.739E-04 3.857E-03 9.080E-02 1.007E+05
1.328E-07 2.735E-07 1.317E+01 5.252E+02 3.375E-07 1.513E+04 3.845E-05 3.041E-01
  SDOT    0.        0.        0.        0.        0.        0.        0.        0.        0.
                     673   639   622   612   605   600   597   617
                     550   549   548   547   547   547   547   608
                     544   544   544   544   544   544   544   600
                     544   544   544   544   544   544   544   593
                     544   544   544   544   544   544   544   587
                     544   544   544   544   544   544   544   582
                                                             569
                                                             548
WTLOSSRATEIS 0.     LBS/SECANDTOTALWTLOSSIS     0.     LBSANDNOSERADIS 2.0800E-02FT
QSTARIS 0.        BTU/LB
                     779   739   707   680   659   641   626   613   603   594   586   580   574
                     569   565   562   559   557   555   553   551   550   549   548   547   547
                     546   546   546   545   545   545   545   545   545   544   544

3.0000000E+00   2.0568970E+00   4.2070977E+04   2.3253199E+05   2.3257503E+05   -2.2708314E+01  6.2783600E+00
```

```
                  5.3070469E-03   1.5201846E+04   1.9812465E+01   1.5881724E+01   1.1877684E-01   6.8991430E+04
                  1.1711304E+02  -1.2579004E+00  -4.4033889E-00   1.2709571E+00   1.8847709E+01   4.4033889E+00
                  1.7582632E+07   1.844120:=-04   1.1733778E+07   2.5409846E+00  -3.2028473E+00  -4.6832509E-01
                  3.3717197E+01  -1.0743991E+02   1.5750261E+03   4.7708987E+04   5.1000000E-01   2.3080000E+01
        1.466E-02 6.739E-04 3.969E-03 8.011E-02 1.200E+05
  1.715E-07 2.823E-07 1.303E+01 5.421E+02 4.110E-07 1.514E+04 3.855E-05 3.824E-01
    SOOT    0.        0.        0.        0.        0.        0.        0.        0.        0.        0.
                        733       682       659       644       634       627       623       639
                        557       554       552       551       551       550       550       629
                        545       545       544       544       544       544       544       620
                        544       544       544       544       544       544       544       612
                        544       544       544       544       544       544       544       605
                        544       544       544       544       544       544       544       600
                                                                                              585
                                                                                              554
    WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
    QSTARIS 0.        BTU/LB
                        839       792       754       724       698       677       658       643       630       618       609       600       593
                        586       581       576       572       568       565       562       559       557       555       554       552       551
                        550       549       548       548       547       547       547       546       546       546       544

    4.0000000E+00   3.5091109E+00   5.6094057E+04   2.2664794E+05   2.2672359E+05  -2.2817118E+01   6.2783600E+00
                  6.5437958E-03   1.5213384E+04   2.5401848E+01   1.5659246E+01   1.0988487E-01   8.5707484E+04
                  1.1761076E+02  -1.0329000E+00  -4.7921722E+00   1.0989069E+00   2.5130669E+01   4.7921722E+00
                  1.7584801E+07   2.4587384E+04   1.1720038E+07   3.0139424E+00  -4.4689798E+00  -4.7838137E-01
                  3.3682934E+01  -1.0741989E+02   1.7024785E+03   6.3971352E+04   5.1000000E-01   2.3080000E+01
        1.469E-02 6.738E-04 4.082E-03 7.097E-02 1.434E+05
  2.195E-07 2.912E-07 1.290E+01 5.589E+02 5.019E-07 1.515E+04 3.865E-05 4.814E-01
    SOOT    0.        0.        0.        0.        0.        0.        0.        0.        0.        0.
                        792       726       695       676       663       654       648       662
                        567       561       558       556       555       554       554       650
                        546       545       545       545       545       545       545       640
                        544       544       544       544       544       544       544       631
                        544       544       544       544       544       544       544       624
                        544       544       544       544       544       544       544       618
                                                                                              601
                                                                                              563
    WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
    QSTARIS 0.        BTU/LB
                        897       842       799       763       734       709       688       670       655       642       630       620       611
                        603       596       590       584       580       575       572       568       565       563       560       558       557
                        555       554       553       552       551       550       550       549       549       549       545

    5.0000000E+00   5.2969119E+00   7.0116701E+04   2.2073285E+05   2.2085044E+05  -2.2924859E+01   6.2783600E+00
                  8.2545272E-03   1.5224966E+04   3.2311199E+01   1.5442451E+01   8.4145357E-02   1.0571933E+05
                  1.1245779E+02   6.9587008E-01   4.6595769E-01  -6.8909516E-01   3.1414152E+01   4.6595769E-01
                  1.7586945E+07   3.0733030E+04   1.1706281E+07   2.9357225E+00   5.5272644E-01  -3.9653444E-01
                  3.3644650E+01  -1.0739988E+02   2.2232554E+03   8.9246683E+04   5.1000000E-01   2.3080000E+01
        1.472E-02 6.738E-04 4.197E-03 6.311E-02 1.719E+05
  2.788E-07 3.000E-07 1.277E+01 5.757E+02 6.143E-07 1.516E+04 3.875E-05 6.068E-01
    SOOT    0.        0.        0.        0.        0.        0.        0.        0.        0.        0.
                        851       770       732       709       693       681       674       685
                        578       569       565       562       560       559       558       671
                        547       546       546       546       545       545       545       660
                        544       544       544       544       544       544       544       650
                        544       544       544       544       544       544       544       642
                        544       544       544       544       544       544       544       635
                                                                                              616
                                                                                              572
    WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
```

```
QSTARIS 0.        BTU/LB
                954     892     842     802     768     741     717     696     679     664     650     638     628
                619     611     604     597     591     586     582     578     574     571     568     565     563
                561     559     558     556     555     554     554     553     553     552     546

  6.0000000E+00  7.6750045E+00   8.4139046E+04   2.1478733E+05   2.1495622E+05   -2.3028772E+01   6.2783600E+00
                 1.1403960E-02   1.5236483E+04   4.0795372E+01   1.5231041E+01    9.0991106E-02   1.2953782E+05
                 1.0859402E-02   1.9306128E+00   4.4308445E+00  -1.9350537E+00    3.7695739E+01   4.4308445E+00
                 1.7589063E+07   3.6878014E+04   1.1692506E+07   5.0081282E+00    6.6360261E+00  -3.3870110E-01
                 3.3614343E+01  -1.0737987E+02   2.0559880E+03   9.6535456E+04    5.1000000E-01   2.3080000E+01
    1.476E-02 6.737E-04 4.315E-03 5.633E-02 2.066E+05
3.515E-07 3.089E-07 1.264E+01 5.923E+02 7.535E-07 1.517E+04 3.885E-05 7.658E-01
  SDOT   0.          0.        0.        0.        0.        0.        0.        0.        0.
                908     814     770     742     723     707     701     768
                591     579     573     569     567     565     564     693
                549     547     547     546     546     546     546     681
                544     544     544     544     544     544     544     670
                544     544     544     544     544     544     544     661
                544     544     544     544     544     544     544     653
                                                                        632
                                                                        583
  WTLOSSRATEIS 0.      LBS/SECANDTOTALWTLOSSIS    0.       LBSANDNOSERADIS 2.0800E-02FT
  QSTARIS 0.        BTU/LB
               1014     942     885     840     802     771     744     722     702     685     670     657     645
                635     625     617     610     603     597     592     587     583     579     576     573     570
                568     565     564     562     561     559     558     558     557     557     548

  7.0000000E+00  1.0867732E+01   9.8161217E+04   2.0881210E+05   2.0904164E+05   -2.3132183E+01   6.2783600E+00
                 1.4311788E-02   1.5247948E+04   5.1148558E+01   1.5024860E+01    7.1107866E-02   1.5773328E+05
                 1.1285241E+02  -3.5497908E-01   2.8073864E-01   3.6746377E-01    4.3979883E+01   2.8073864E-01
                 1.7591156E+07   4.3022190E+04   1.1678716E+07   3.9271980E+00    5.2716463E-01  -4.0779878E-01
                 3.3580013E+01  -1.0735987E+02   2.6308850E+03   1.1283800E+05    5.1000000E-01   2.3080000E+01
    1.479E-02 6.737E-04 4.434E-03 3.044E-02 2.490E+05
4.400E-07 3.179E-07 1.252E+01 6.089E+02 9.262E-07 1.518E+04 3.896E-05 9.678E-01
  SDOT   0.          0.        0.        0.        0.        0.        0.        0.        0.
                960     860     808     776     754     738     728     732
                603     590     582     577     574     572     570     716
                551     549     548     548     547     547     547     702
                545     544     544     544     544     544     544     690
                544     544     544     544     544     544     544     680
                544     544     544     544     544     544     544     672
                                                                        648
                                                                        595
  WTLOSSRATEIS 0.      LBS/SECANDTOTALWTLOSSIS    0.       LBSANDNOSERADIS 2.0800E-02FT
  QSTARIS 0.        BTU/LB
               1082     999     932     879     837     802     772     747     725     706     689     675     662
                650     640     631     622     615     608     602     597     592     588     584     580     577
                574     572     570     568     566     565     564     563     562     562     550
    TIME             X                   Y                 Z                 ALT               GAMMA             VMAS
                     PSI.                VEL               QD                AMACH             CD                REN
                     PHI                 THETA             ALPHA             BET               PS                ALPT
                     XF                  YE                ZE                FD                FN                GFZ
                     LAT                 LONG              BETA              QCIR              IZ                IX

  8.0000000E+00  1.4381999E+01   1.1218285E+05   2.0230641E+05   2.0310596E+05   -2.3241265E+01   6.2783600E+00
                 1.3913329E-02   1.5259356E+04   6.2711759E+01   1.4823682E+01    7.5689961E-02   1.9094836E+05
                 1.1691851E+02  -2.1344005E+00  -3.6709559E+00   2.1622500E+00    5.0261390E+01   3.6709599E+00
                 1.7593225E+07   4.9165840E+04   1.1664908E+07   5.2070247E+00   -8.5863763E+00  -4.7849860E-01
                 3.3545661E+01  -1.0733988E+02   2.4716173E+03   1.2915369E+05    5.1000000E-01   2.3080000E+01
```

```
      1.482E-02 6.737E-04 4.555E-03 4.531E-02 3.008E+05
5.472E-07 3.268E-07 1.239E+01 6.254E+02 1.141E-06 1.519E+04 3.906E-05 1.224E+00
   SDOT   0.          0.        0.        0.        0.        0.        0.        0.        0.
                            1011      906       849       812       787       768       757       758
                             615      601       592       586       582       579       577       740
                             553      551       550       549       549       548       548       724
                             545      545       545       545       544       544       544       711
                             544      544       544       544       544       544       544       700
                             544      544       544       544       544       544       544       690
                                                                                                  665
                                                                                                  608
 WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
 QSTARIS 0.          BTU/LB                                                                       709       692       673
                            1159     1061       984       923       874       834       801       772       748       727       592       588       585
                             666      654       644       635       627       619       613       607       602       597       553
                             582      579       577       574       573       571       570       569       568       567

 9.0000000E+00       1.7789750E+01       1.2620338E+05       1.9676939E+05       1.9714832E+05       -2.3349328E+01       6.2783600E+00
                     1.4989356E-02       1.5270724E+04       7.8877520E+01       1.4627318E+01       6.4943661E-02       2.2990097E+05
                     1.1172372E+02       1.5733595E+00       1.6204045E+00       -1.5557048E+00       5.6544901E+01       1.6204045E+00
                     1.7595266E+07       5.5309104E+04       1.1651083E+07       5.5312306E+00       4.6923173E+00       -3.9751216E-01
                     3.3511288E+01       -1.0731990E+02      2.8805986E+03       1.4548170E+05       5.1000000E-01       2.3080000E+01
      1.485E-02 6.736E-04 4.678E-03 4.082E-02 3.643E+05
6.765E-07 3.358E-07 1.227E+01 6.419E+02 1.408E-06 1.521E+04 3.917E-05 1.551E+00
   SDOT   0.          0.        0.        0.        0.        0.        0.        0.        0.
                            1061      949       890       850       822       800       788       785
                             628      613       603       596       591       587       585       764
                             556      554       552       551       550       550       550       747
                             545      545       545       545       545       545       545       732
                             544      544       546       544       544       544       544       720
                             544      544       544       544       544       544       544       710
                                                                                                  681
                                                                                                  622
 WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
 QSTARIS 0.          BTU/LB                                                                                 728       711       695
                            1244     1130      1041       970       914       868       830       799       772       749       601       597       593
                             681      669       658       648       639       631       623       617       611       606       557
                             589      586       584       581       579       577       576       575       574       573

 1.0000000E+01       2.2179234E+01       1.4022331E+05       1.9070245E+05       1.9117014E+05       -2.3450480E+01       6.2783600E+00
                     2.0681793E-02       1.5281929E+04       9.7086730E+01       1.4435528E+01       6.0280826E-02       2.7536953E+05
                     1.1211026E+02       6.5057488E-01       1.3379386E+00       -6.3675739E-01      6.2827999E+01       1.3379386E+00
                     1.7597283E+07       6.1451221E+04       1.1637242E+07       6.3193270E+00       4.7687739E+00       -4.0767238E-01
                     3.3476892E+01       -1.0729992E+02      3.1034183E+03       1.6182328E+05       5.1000000E-01       2.3080000E+01
      1.488E-02 6.736E-04 4.803E-03 3.688E-02 4.424E+05
8.314E-07 3.448E-07 1.215E+01 6.583E+02 1.742E-06 1.522E+04 3.928E-05 1.967E+00
   SDOT   0.          0.        0.        0.        0.        0.        0.        0.        0.
                            1111      993       931       889       858       834       821       813
                             640      624       614       607       601       597       594       790
                             559      556       554       553       552       552       551       771
                             546      546       545       545       545       545       545       755
                             544      544       544       544       544       544       544       741
                             544      544       544       544       544       544       544       730
                                                                                                  699
                                                                                                  636
 WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
 QSTARIS 0.          BTU/LB                                                                                 749       729       712
                            1341     1204      1102      1022       957       905       862       827       797       771       610       605       601
                             697      683       671       661       651       642       634       627       621       615       561
                             597      594       591       588       586       584       582       581       580       579
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1.1000000E+01    2.7141567E+01    1.5424243E+05    1.8460552E+05    1.8517134E+05   -2.3559782E+01    6.2783600E+00
                 1.8471117E-02    1.5293069E+04    1.1884707E+02    1.4248242E+01    5.9491363E-02    3.2822690E+05
                 1.1607068E+02   -2.1130559E+00   -2.5018530E+00    2.1425745E+00    6.9110021E+01    2.5018530E+00
                 1.7599275E+07    6.7592472E+04    1.1623385E+07    7.6343865E+00   -1.0915935E+01   -4.7727204E-01
                 3.3442475E+01   -1.0727995E+02    3.1446013E+03    1.7817803E+05    5.1000000E-01    2.3080000E+01
      1.492E-02 6.735E-04 4.931E-03 3.341E-02 5.383E+05
  1.016E-06 3.539E-07 1.203E+01 6.747E+02 2.158E-06 1.523E+04 3.940E-05 2.498E+00
   SDOT    0.           0.          0.          0.          0.          0.          0.          0.          0.
                 1164    1036    971    928    898    870    855    843
                  653     635    625    618    612    607    604    818
                  563     559    557    556    555    554    553    796
                  547     546    546    546    545    545    545    778
                  544     544    544    544    544    544    544    763
                  544     544    544    544    544    544    544    750
                                                                     716
 WTLOSSRATEIS 0.         LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT    651
 QSTARIS 0.           BTU/LB
                 1449    1285   1167   1076   1003    944    895    856    822    794    770    748    730
                  713     698    685    674    663    654    645    638    631    624    619    614    609
                  605     601    598    595    593    591    589    588    587    586    566

1.2000000E+01    3.1786459E+01    1.6826006E+05    1.7847741E+05    1.7915075E+05   -2.3664901E+01    6.2783600E+00
                 2.2284869E-02    1.5304098E+04    1.4473834E+02    1.4065223E+01    5.5970818E-02    3.8944601E+05
                 1.1127757E+02    2.5862578E+00    2.3753990E+00   -2.5791627E+00    7.5392619E+01    2.3753990E+00
                 1.7601239E+07    7.3733342E+04    1.1609511E+07    8.7486103E+00    1.2622077E+01   -4.0619489E-01
                 3.3408038E+01   -1.0725998E+02    3.3419180E+03    1.9454468E+05    5.1000000E-01    2.3080000E+01
      1.495E-02 6.735E-04 5.060E-03 3.034E-02 6.566E+05
  1.236E-06 3.630E-07 1.191E+01 6.910E+02 2.679E-06 1.524E+04 3.952E-05 3.177E+00
   SDOT    0.           0.          0.          0.          0.          0.          0.          0.          0.
                 1220    1081   1012    967    933    906    891    876
                  667     647    636    628    622    617    614    846
                  567     563    560    559    557    556    556    822
                  547     547    546    546    546    546    546    802
                  544     544    544    544    544    544    544    785
                  544     544    544    544    544    544    544    772
                                                                     734
 WTLOSSRATEIS 0.         LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT    666
 QSTARIS 0.           BTU/LB
                 1567    1375   1237   1134   1052    985    931    886    849    818    791    768    748
                  730     714    700    687    676    665    656    648    641    634    628    622    618
                  613     609    606    603    600    598    596    595    593    593    570

1.3000000E+01    3.7894799E+01    1.8227671E+05    1.7231992E+05    1.7311017E+05   -2.3769558E+01    6.2783600E+00
                 2.3873710E-02    1.5314961E+04    1.7734569E+02    1.3886334E+01    5.1984653E-02    4.7031510E+05
                 1.1577706E+02   -2.5629488E+00   -1.9942149E+00    2.5965809E+00    8.1675520E+01    1.9942149E+00
                 1.7403180E+07    7.9872485E+04    1.1595622E+07    9.9546854E+00   -1.2983843E+01   -4.8414961E-01
                 3.3373578E+01   -1.0724003E+02    3.5986894E+03    2.1092497E+05    5.1000000E-01    2.3080000E+01
      1.498E-02 6.735E-04 5.191E-03 2.728E-02 8.190E+05
  1.512E-06 3.680E-07 1.179E+01 6.992E+02 3.370E-06 1.525E+04 3.963E-05 4.043E+00
   SDOT    0.           0.          0.          0.          0.          0.          0.          0.          0.
                 1279    1128   1054   1006    971    943    927    910
                  681     659    647    639    633    627    624    877
                  571     566    563    562    560    559    558    850
                  548     568    547    557    546    546    546    827
                  544     544    544    544    544    544    544    809
                  544     544    544    544    544    544    544    794
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                                                                                         753
                                                                                         683
WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS   0.       LBSANDNOSERADIS 2.0800E-02FT
QSTARIS 0.          BTU/LB
                         1700   1474   1312   1194   1103   1029    968    918    877    843    813    788    766
                          746    729    714    701    688    677    668    659    651    644    637    631    626
                          621    617    614    610    608    605    603    602    600    599    576

1.4000000E+01    4.3343126E+01    1.9629149E+05    1.6613146E+05    1.6704801E+05   -2.3976507E+01    6.2783600E+00
                 2.5599236E-02    1.5325611E+04    2.2123579E+02    1.3856791E+01    4.8235510E-02    5.8630253E+05
                 1.1208902E+02    2.6024628E+00    1.7731313E+00   -2.5902184E+00    8.7958310E+01    1.7731313E+00
                 1.7605094E+07    8.6011395E+04    1.1581716E+07    1.1522694E+01    1.4401474E+01   -4.3308828E-01
                 3.3339099E+01   -1.0722008E+02    3.8784004E+03    2.2731668E+05    5.1000000E-01    2.3080000E+01
   1.499E-02 6.735E-04 5.213E-03 2.418E-02 1.060E+06
1.884E-06 3.680E-07 1.178E+01 6.985E+02 4.354E-06 1.526E+04 3.974E-05 5.219E+00
   SDOT   0.        0.        0.        0.        0.        0.        0.        0.        0.
                         1342   1179   1099   1048   1011    982    965    949
                          696    671    658    649    643    638    634    911
                          576    570    567    565    563    562    561    880
                          549    548    548    547    547    547    547    855
                          545    545    544    544    544    544    544    834
                          544    544    544    544    544    544    544    817
                                                                         772
                                                                         699
WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS   0.       LBSANDNOSERADIS 2.0800E-02FT
QSTARIS 0.          BTU/LB
                         1850   1581   1395   1259   1156   1075   1008    952    907    869    836    809    785
                          764    745    729    714    701    690    679    670    661    654    647    640    635
                          630    626    622    618    615    613    611    609    607    607    582

1.5000000E+01    5.0261525E+01    2.1030477E+05    1.5991357E+05    1.6096582E+05   -2.3982365E+01    6.2783600E+00
                 2.4818769E-02    1.5335992E+04    2.7621350E+02    1.3866177E+01    4.4722456E-02    7.3150487E+05
                 1.1544582E+02   -2.1510748E+00   -1.4502537E+00    2.1832316E+00    9.4241271E+01    1.4502537E+00
                 1.7606982E+07    9.2148322E+04    1.1567795E+07    1.3338356E+01   -1.4706170E+01   -4.9568730E-01
                 3.3304599E+01   -1.0720014E+02    4.1830579E+03    2.4372149E+05    5.1000000E-01    2.3080000E+01
   1.498E-02 6.735E-04 5.206E-03 2.144E-02 1.374E+06
2.149E-06 3.680E-07 1.178E+01 6.987E+02 5.644E-06 1.527E+04 3.986E-05 6.767E+00
   SDOT   0.        0.        0.        0.        0.        0.        0.        0.        0.
                         1411   1235   1148   1093   1053   1023   1005    992
                          712    684    670    660    653    648    645    948
                          580    574    571    568    567    565    564    912
                          551    549    549    548    548    548    547    884
                          545    545    545    545    544    544    544    860
                          544    544    544    544    544    544    544    841
                                                                         792
                                                                         717
W       ATEIS 0.       LBS/SECANDTOTALWTLOSSIS   0.       LBSANDNOSERADIS 2.0800E-02FT
Q     S 0.          BTU/LB
                         2025   1700   1485   1328   1212   1122   1049    988    937    895    860    830    804
                          782    762    744    728    715    702    691    681    672    664    656    650    644
                          639    634    630    626    623    620    618    616    615    614    588
     TIME          X                 Y                 Z                 ALT               GAMMA             VMAS
                   PSI.              VEL               QD                AMACH             CD                REN
                   PHI               THETA             ALPHA             BET               PS                ALPT
                   XF                YE                ZE                FD                FN                GFZ
                   LAT               LONG              BETA              GCIR              IZ                IX

1.6000000E+01    5.4861058E+01    2.2431570E+05    1.5366519E+05    1.5486254E+05   -2.4085095E+01    6.2783600E+00
                 1.3477400E-02    1.5346097E+04    3.4571440E+02    1.3875314E+01    4.0439118E-02    9.1525871E+05
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                1.1368979E+02    2.0678500E-01    3.9423557E-01   -1.7078043E-01    1.0052448E+02    3.9423557E-01
                1.7608845E+07    9.8284511E+04    1.1553858E+07    1.5095618E+01    5.0036158E+00   -4.7651382E-01
                3.3270080E+01   -1.0718020E+02    4.6261300E+03    2.6013750E+05    5.1000000E-01    2.3080000E+01
      1.498E-02 6.735E-04 5.199E-03 1.498E-02 1.783E+06
2.936E-06 3.679E-07 1.179E+01 6.990E+02 7.321E-06 1.528E+04 3.999E-05 8.780E+00
    SOOT    0.          0.        0.        0.        0.        0.        0.        0.        0.
                      1486      1207      1202      1142      1099      1066      1040      1041
                       728       698       682       672       664       658       655       989
                       586       578       575       572       570       568       568       940
                       552       550       550       549       549       548       548       915
                       545       545       545       545       545       545       545       889
                       544       544       544       544       544       544       544       867
                                                                                          813
                                                                                          735
    WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
    OSTARIS 0.          BTU/LB
                      2239      1838      1584      1405      1273      1172      1091      1025       969       923       885       852       824
                       800       778       759       743       728       715       703       692       683       674       666       659       653
                       647       642       638       634       631       628       628       624       622       621       594

    1.7000000E+01   6.3884691E+01    2.3832423E+05    1.4738711E+05    1.4873896E+05   -2.4193581E+01    6.2783600E+00
                2.9740488E-02    1.5355832E+04    4.4209780E+02    1.3984111E+01    3.8564008E-02    1.1509423E+06
                1.1324731E+02    2.3936146E+00    9.2985087E-01   -2.3733225E+00    1.0680685E+02    9.2985087E-01
                1.7610681E+07    1.0441926E+05    1.1539907E+07    1.8409087E+01    1.5091845E+01   -4.8583327E-01
                3.3235543E+01   -1.0716028E+02    4.8510681E+03    2.7686510E+05    5.1000000E-01    2.3080000E+01
      1.496E-02 6.735E-04 5.119E-03 1.849E-02 2.412E+06
3.750E-06 3.619E-07 1.186E+01 6.867E+02 9.762E-06 1.529E+04 4.012E-05 1.150E+01
    SOOT    0.          0.        0.        0.        0.        0.        0.        0.        0.
                      1569      1364      1262      1197      1150      1114      1095      1099
                       746       712       695       684       675       669       665      1038
                       591       583       579       576       574       572       571       989
                       553       552       551       550       550       549       549       950
                       545       545       545       545       545       545       545       920
                       545       545       544       544       544       544       544       895
                                                                                          835
                                                                                          753
    WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
    OSTARIS 0.          BTU/LB
                      2511      2002      1695      1489      1338      1224      1136      1063      1003       953       910       875       845
                       818       795       775       757       742       728       715       704       693       684       676       669       662
                       656       651       646       642       639       636       633       631       630       629       600

    1.8000000E+01   7.1728240E+01    2.5232985E+05    1.4107951E+05    1.4259525E+05   -2.4299920E+01    6.2783600E+00
                2.7031111E-02    1.5365015E+04    5.6865923E+02    1.4143610E+01    3.4902313E-02    1.5540608E+06
                1.1428334E+02    7.7199140E-01    1.1111727E-02   -7.4745812E-01    1.1308992E+02    1.1111727E-02
                1.7612492E+07    1.1055200E+05    1.1525941E+07    2.1430784E+01    2.3197668E-01   -5.1734083E-01
                3.3200980E+01   -1.0714036E+02    5.3600064E+03    2.9300400E+05    5.1000000E-01    2.3080000E+01
      1.493E-02 6.735E-04 5.004E-03 1.429E-02 3.264E+06
4.817E-06 3.559E-07 1.196E+01 6.766E+02 1.305E-05 1.530E+04 4.027E-05 1.515E+01
    SOOT    0.          0.        0.        0.        0.        0.        0.        0.        0.
                      1660      1440      1329      1258      1208      1169      1147      1167
                       764       728       709       696       687       680       676      1094
                       597       588       583       580       578       576       575      1036
                       555       553       552       551       551       550       550       991
                       546       545       545       545       545       545       545       955
                       545       545       545       544       544       544       544       926
                                                                                          858
                                                                                          773
    WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
    OSTARIS 0.          BTU/LB
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                    2800    2209    1828    1584    1411    1282    1183    1104    1038     983     937     899     866
                     837     813     791     772     756     741     727     715     704     695     686     678     671
                     665     660     655     651     647     644     641     639     637     636     607

   1.9000000E+01   7.9897015E+01   2.6633190E+05   1.3474244E+05   1.3643146E+05  -2.4404908E+01   6.2783600E+00
                   2.7930974E-02   1.5373523E+04   7.3591308E+02   1.4306487E+01   3.3113305E-02   2.0444751E+06
                   1.1464807E+02  -2.5029848E-02  -2.4267724E-01   5.2375482E-02   1.1937266E+02   2.4267724E-01
                   1.7014277E+07   1.1668289E+05   1.1511960E+07   2.6312421E+01  -6.5564120E+00  -5.4730140E-01
                   3.3166417E+01  -1.0712046E+02   5.6495907E+03   3.0945319E+05   5.1000000E-01   2.3080000E+01
     1.491E-02 6.736E-04 4.891E-03 1.234E-02 4.423E+06
 6.227E-06 3.499E-07 1.207E+01 6.664E+02 1.747E-05 1.531E+04 4.045E-05 1.998E+01
   SDOT   0.          0.          0.          0.          0.          0.          0.          0.          0.
                    1760    1523    1403    1327    1271    1229    1205    1246
                     783     744     723     710     700     693     688    1157
                     604     594     588     585     582     580     579    1089
                     557     555     553     553     552     551     551    1036
                     546     546     545     545     545     545     545     994
                     545     545     545     545     545     545     545     961
                                                                             882
                                                                             793
   WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS   0.        LBSANDNOSERADIS 2.0800E-02FT
   QSTARIS 0.          BTU/LB
                    3132    2457    1982    1690    1492    1344    1233    1146    1075    1016     965     923     888
                     857     831     808     788     770     754     740     727     716     705     696     688     681
                     674     669     663     659     655     652     649     647     645     644     614

   2.0000000E+01   8.8287010E+01   2.8032984E+05   1.2837622E+05   1.3024791E+05  -2.4510096E+01   6.2783600E+00
                   2.9815136E-02   1.5381222E+04   9.5840984E+02   1.4472719E+01   3.0976847E-02   2.7078258E+06
                   1.1452332E+02   9.2560599E-01  -2.0610044E-02  -8.9833741E-01   1.2565540E+02   2.0610044E-02
                   1.7614035E+07   1.2281168E+05   1.1497967E+07   3.2056798E+01  -7.2517155E-01  -5.7375907E-01
                   3.3131832E+01  -1.0710056E+02   6.0392402E+03   3.2591181E+05   5.1000000E-01   2.3080000E+01
     1.480E-02 6.736E-04 4.779E-03 1.061E-02 6.004E+06
 8.102E-06 3.439E-07 1.217E+01 6.561E+02 2.342E-05 1.532E+04 4.066E-05 2.637E+01
   SDOT   0.          0.          0.          0.          0.          0.          0.          0.          0.
                    1871    1614    1485    1402    1342    1296    1270    1337
                     804     761     739     725     714     706     701    1228
                     611     599     593     589     586     584     583    1148
                     559     556     555     554     553     553     552    1006
                     546     546     546     546     545     545     545    1037
                     545     545     545     545     545     545     545     999
                                                                             908
                                                                             814
   WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS   0.        LBSANDNOSERADIS 2.0800E-02FT
   QSTARIS 0.          BTU/LB
                    3514    2732    2172    1814    1581    1414    1288    1191    1114    1049     995     949     910
                     878     849     825     803     784     767     752     739     727     716     707     698     690
                     684     678     672     668     663     660     657     655     653     652     621

   2.1000000E+01   9.7080557E+01   2.9432218E+05   1.2198129E+05   1.2404503E+05  -2.4614451E+01   6.2783600E+00
                   3.9468349E-02   1.5387823E+04   1.2564151E+03   1.4642157E+01   2.9572044E-02   3.6116457E+06
                   1.1432710E+02   1.8568285E+00   2.7151229E-01  -1.8234086E+00   1.3193808E+02   2.7151229E-01
                   1.7617767E+07   1.2893783E+05   1.1483962E+07   4.0118844E+01   1.2523719E+01  -6.1055112E-01
                   3.3097234E+01  -1.0708068E+02   6.3261308E+03   3.4237897E+05   5.1000000E-01   2.3080000E+01
     1.485E-02 6.736E-04 4.669E-03 9.092E-03 8.163E+06
 1.061E-05 3.379E-07 1.228E+01 6.456E+02 3.145E-05 1.532E+04 4.091E-05 3.484E+01
   SDOT   0.          0.          0.          0.          0.          0.          0.          0.          0.
                    1991    1715    1575    1485    1420    1370    1341    1443
                     826     780     756     740     729     720     715    1309
                     618     605     599     595     591     589     587    1213
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                     561    558    556    555    555    554    554   1140
                     547    545    546    546    546    546    546   1084
                     546    545    545    545    545    545    545   1040
                                                                      936
                                                                      837
WTLOSSRATEIS 0.      LBS/SECANDTOTALWTLOSSIS    0.      LBSANDNOSERADIS 2.0800E-02FT
QSTARIS 0.       BTU/LB
                    3926   3042   2403   1960   1682   1491   1348   1240   1154   1085   1026    976    934
                     899    869    842    819    799    781    765    751    739    727    717    708    700
                     693    687    681    676    672    668    665    663    661    660    628

 2.2000000E+01   1.0674528E+02   3.0830839E+05   1.1555825E+05   1.1782338E+05  -2.4718548E+01   6.2783600E+00
                 4.0567211E-02   1.5393041E+04   1.6583860E+03   1.4814638E+01   2.7839914E-02   4.8524564E+06
                 1.1477279E+02  -1.6840097E+00  -3.8427284E-02   1.7212835E+00   1.3822092E+02   3.8427284E-02
                 1.7619473E+07   1.3506043E+05   1.1469945E+07   4.9852307E+01  -2.3395696E+00  -6.6581305E-01
                 3.3062627E+01  -1.0706081E+02   6.7197269E+03   3.5885364E+05   5.1000000E-01   2.3080000F+01
        1.482E-02 6.737E-04 4.561E-03 7.757E-03 1.112E+07
1.400E-05 3.318E-07 1.239E+01 6.351E+02 4.229E-05 1.533E+04 4.118E-05 4.609E+01
  SDOT   0.         0.        0.        0.        0.        0.        0.        0.        0.
                    2124   1825   1674   1576   1506   1451   1420   1563
                     851    800    774    757    745    735    730   1400
                     626    612    605    600    597    594    592   1284
                     563    560    558    557    556    555    555   1200
                     547    547    546    546    546    546    546   1135
                     546    545    545    545    545    545    515   1085
                                                                      967
                                                                      860
WTLOSSRATEIS 0.      LBS/SECANDTOTALWTLOSSIS    0.      LBSANDNOSERADIS 2.0800E-02FT
QSTARIS 0.       BTU/LB
                    4390   3396   2663   2133   1797   1575   1414   1292   1198   1122   1059   1005    959
                     921    888    860    836    814    795    779    764    750    739    728    718    710
                     703    696    690    685    680    677    673    671    669    668    636

 2.3000000E+01   1.1609612E+02   3.2228667E+05   1.0910768E+05   1.1158354E+05  -2.4825204E+01   6.2783600E+00
                 4.4439153E-02   1.5396358E+04   2.2045428E+03   1.4989768E+01   2.6548792E-02   6.5693196E+06
                 1.1476330E+02   1.4273871E+00   4.8749256E-02  -1.3875829E+00   1.4450371E+02   4.8749256E-02
                 1.7621152E+07   1.4117983E+05   1.1455918E+07   6.3196796E+01   3.9454560E+00  -7.3172447E-01
                 3.3028014E+01  -1.0704096E+02   7.0465211E+03   3.7533334E+05   5.1000000E-01   2.3080000E+01
        1.479E-02 6.737E-04 4.455E-03 6.588E-03 1.516E+07
1.860E-05 3.258E-07 1.249E+01 6.245E+02 5.694E-05 1.533E+04 4.149E-05 6.101E+01
  SDOT   0.         0.        0.        0.        0.        0.        0.        0.        0.
                    2275   1944   1781   1676   1599   1540   1507   1700
                     878    822    794    775    762    752    746   1503
                     634    619    611    606    602    599    597   1364
                     566    562    560    559    558    557    556   1264
                     548    547    547    547    546    546    546   1190
                     546    546    546    545    545    545    545   1133
                                                                      998
                                                                      860
WTLOSSRATEIS 0       LBS/SECANDTOTALWTLOSSIS    0.      LBSANDNOSERADIS 2.0800E-02FT
QSTARIS 0.       BTU/LB
                    4905   3784   2950   2346   1934   1671   1488   1349   1244   1161   1092   1035    986
                     944    909    879    853    830    810    792    776    762    750    739    729    720
                     712    705    699    694    689    685    682    679    677    676    643
   TIME          X              Y              Z              ALT            GAMMA          VMAS
                 PSI.           VEL            QD             AMACH          CD             REN
                 PHI            THETA          ALPHA          BET            PS             ALPT
                 XF             YE             ZE             FD             FN             GFZ
                 LAT            LONG           BETA           QCIW           IZ             IX

 2.4000000E+01   1.2614421E+02   3.3625501E+05   1.0263060E+05   1.0532647E+05  -2.4930328E+01   6.2783600E+00
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                  4.0124096E-02    1.5396306E+04    2.9518186E+03    1.5160182E+01    4.2038934E-02    8.9636736E+06
                  1.1508015E+02    1.4418523E+00   -1.6365821E-01   -1.4039187E+00    1.5078658E+02    1.6365821E-01
                  1.7622804E+07    1.4729423E+05    1.1441884E+07    1.3399022E+.     -1.7735283E+01   -1.0872022E+00
                  3.2993400E+01   -1.0702112E+02    4.4500800E+03    3.9181632E+05    5.1000000E-01    2.3080000E+01
      1.477E-02 6.737E-04 4.352E-03 2.197E-02 2.071E+07
2.491E-05 3.197E-07 1.260E+01 6.137E+02 7.676E-05 1.533E+04 4.184E-05 8.084E+01
   SOOT    0.          0.          0.          0.          0.          0.          0.          0.          0.
                     2445     2075     1899     1785     1702     1638     1602     1856
                      911      849      815      795      781      769      763     1616
                      643      627      618      612      608      605      603     1452
                      568      564      562      561      559      559      558     1334
                      548      548      547      547      547      547      546     1248
                      547      546      546      546      546      545      545     1183
                                                                                  1029
                                                                                   860
   WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
   OSTARIS 0.          BTU/LB
                     5474     4215     3280     2592     2093     1778     1567     1413     1295     1203     1128     1066     1014
                      969      931      898      870      844      825      806      789      775      761      750      739      730
                      722      715      708      703      698      694      690      687      685      684      651

   2.5000000E+01  1.3665546E+02    3.5020577E+05    9.6130472E+04    9.9055803E+04   -2.5036367E+01    6.2783600E+00
                  4.9753359E-02    1.5384147E+04    3.9774748E+03    1.5335136E+01    4.0190298E-02    1.2322995E+07
                  1.1506981E+02    8.9376847E-01   -4.2044376E-02   -8.4830440E-01    1.5706941E+02    4.2044376E-02
                  1.7624429E+07    1.5340054E+05    1.1427851E+07    1.7260780E+02   -6.1394013E+00   -1.2782149E+00
                  3.2958804E+01   -1.0700132E+02    4.6547706E+03    4.0829344E+05    5.1000000E-01    2.3080000E+01
      1.474E-02 6.738E-04 4.257E-03 2.044E-02 2.831E+07
3.361E-05 3.136E-07 1.271E+01 6.028E+02 1.036E-04 1.532E+04 4.222E-05 1.071E+02
   SOOT    0.          0.          0.          0.          0.          0.          0.          0.          0.
                     2634     2222     2024     1903     1814     1744     1705     2035
                      948      871      837      816      800      788      781     1740
                      651      638      625      619      615      611      609     1547
                      571      567      564      563      561      560      560     1410
                      549      548      548      547      547      547      547     1310
                      547      546      546      546      546      546      546     1236
                                                                                  1060
                                                                                   860
   WTLOSSRATEIS 0.        LBS/SECANDTOTALWTLOSSIS    0.        LBSANDNOSERADIS 2.0800E-02FT
   OSTARIS 0.          BTU/LB
                     6102     4693     3643     2858     2289     1907     1658     1483     1349     1247     1166     1099     1043
                      995      953      918      889      863      840      820      803      787      773      761      750      740
                      732      724      717      712      707      702      699      696      694      692      659

   2.6000000E+01  1.4760915E+02    3.6413043E+05    8.9611334E+04    9.2774800E+04   -2.5138585E+01    6.2783578E+00
                  1.0211939E-02    1.5364720E+04    5.3980940E+03    1.5501141E+01    3.8598569E-02    1.7087774E+07
                  1.1510634E+02   -5.4201152E-01    3.0386823E-02    5.7623229E-01    1.6335230E+02    3.0386823E-02
                  1.7626024E+07    1.5949499E+05    1.1413025E+07    2.2497974E+02    7.6073481E+00   -1.5380598E+00
                  3.2974247E+01   -1.0698155E+02    4.8467227E+03    4.2475465E+05    5.1000000E-01    2.3080000E+01
      1.472E-02 6.971E-04 4.166E-03 1.895E-02 3.874E+07
4.573E-05 3.075E-07 1.281E+01 5.913E+02 1.399E-04 1.530E+04 4.268E-05 1.419E+02
   SOOT    0.          0.          0.          0.          0.          0.          0.          0.          2.364E-04
                     2844     2388     2168     2031     1934     1860     1817     2251
                      991      902      862      838      822      807      801     1884
                      660      643      633      626      621      618      615     1652
                      574      569      567      565      563      562      562     1493
                      550      549      548      548      548      547      547     1377
                      548      547      547      546      546      546      546     1291
                                                                                  1060
                                                                                   860
   WTLOSSRATEIS 1.8444E-04LBS/SECANDTOTALWTLOSSIS    6.9916E-05LBSANDNOSERADIS 2.1208E-02FT
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QSTARIS 0.        BTU/LB
                         6400    5130    4021    3159    2520    2052    1759    1558    1410    1295    1206    1133    1073
                         1021     977     940     907     880     856     835     816     800     785     772     761     751
                          742     734     727     721     716     711     707     704     702     700     666

  2.7000000E+01   1.5877802E+02   3.7802130E+05   8.3076808E+04   8.6406900E+04  -2.5243955E+01   6.2783508E+00
                  4.1500352E-02   1.5335547E+04   7.3783347E+03   1.5661462E+01   3.7255702E-02   2.3922539E+07
                  1.1509979E+02  -6.6634532E-01   1.5180525E-01   7.0229355E-01   1.6963527E+02   1.5180525E-01
                  1.7627590E+07   1.6557444E+05   1.1399817E+07   2.9681296E+02   4.1120256E+01  -1.8935680E+00
                  3.2889748E+01  -1.0696184E+02   5.0214155E+03   4.4119071E+05   5.1000000E-01   2.3080000E+01
    1.469E-02 7.827E-04 4.081E-03 1.747E-02 5.312E+07
6.275E-05 3.014E-07 1.290E+01 5.796E+02 1.890E-04 1.527E+04 4.324E-05 1.880E+02
  SDOT   0.          0.        0.        0.        0.        0.        0.          0.          9.9792-04
                         3075    2571    2326    2173    2065    1984    1938    2517
                         1041     938     891     864     845     831     823    2050
                          669     652     641     634     629     625     622    1767
                          577     572     569     567     566     565     564    1581
                          551     549     549     548     548     548     548    1446
                          548     547     547     547     547     546     546    1345
                                                                                 1060
                                                                                  860
  WTLOSSRATEIS 3.6534E-04LBS/SECANDTOTALWTLOSSIS   2.9515E-04LBSANDNOSERADIS 2.2499E-02FT
  QSTARIS 0.        BTU/LB
                         6400    5400    4321    3440    2746    2225    1876    1643    1476    1347    1249    1170    1104
                         1049    1002     962     927     898     872     850     830     813     798     784     772     761
                          752     744     736     730     725     720     716     713     711     709     674

  2.8000000E+01   1.7012604E+02   3.9186813E+05   7.6531839E+04   8.0197398E+04  -2.5353572E+01   6.2783402E+00
                  5.1463755E-02   1.5293335E+04   1.0059212E+04   1.5790744E+01   3.6036543E-02   3.3294739E+07
                  1.1557721E+02   7.3818665E-01  -2.3109357E-01  -6.8920536E-01   1.7591830E+02   2.3109357E-01
                  1.7629125E+07   1.7163442E+05   1.1335835E+07   3.9141623E+02  -8.5341934E+01  -2.3694359E+00
                  3.2855333E+01  -1.0694219E+02   5.1912873E+03   4.5758942E+05   5.1000000E-01   2.3080000E+01
    1.467E-02 9.232E-04 4.014E-03 1.610E-02 7.176E+07
8.602E-05 2.969E-07 1.298E+01 5.723E+02 2.528E-04 1.523E+04 4.380E-05 2.483E+02
  SDOT   0.          0.        0.        0.        0.        0.        0.          0.          2.150E-03
                         3326    2774    2503    2332    2212    2120    2070    2787
                         1097     979     925     893     871     855     846    2251
                          679     660     650     642     637     632     630    1901
                          581     575     572     570     568     567     566    1676
                          551     550     550     549     549     548     548    1518
                          549     548     547     547     547     547     547    1399
                                                                                 1060
                                                                                  860
  WTLOSSRATEIS 4.0673E-04LBS/SECANDTOTALWTLOSSIS   6.3579E-04LBSANDNOSERADIS 2.4460E-02FT
  QSTARIS 0.        BTU/LB
                         6400    5678    4587    3689    2965    2409    2002    1734    1546    1404    1295    1208    1137
                         1078    1028     985     948     916     889     865     844     826     810     796     783     772
                          762     754     746     739     734     729     725     722     719     717     683

  2.9000000E+01   1.8196328E+02   4.0565749E+05   6.9982752E+04   7.3911977E+04  -2.5459965E+01   6.2783260E+00
                  5.3072215E-02   1.5234616E+04   1.3472759E+04   1.5730115E+01   3.4943276E-02   4.4946754E+07
                  1.1566712E+02   5.7503922E-01  -2.1285998E-01  -5.2481526E-01   1.8220139E+02   2.1285998E-01
                  1.7630628E+07   1.7766876E+05   1.1371893E+07   5.0833721E+02  -1.0528372E+02  -2.9496750E+00
                  3.2821036E+01  -1.0692263E+02   5.3536948E+03   4.7393499E+05   5.1000000E-01   2.3080000E+01
    1.468E-02 1.130E-03 4.045E-03 1.480E-02 9.365E+07
1.161E-04 2.969E-07 1.294E+01 5.711E+02 3.294E-04 1.517E+04 4.540E-05 3.228E+02
  SDOT   0.          0.        0.        0.        0.        0.        0.          0.          3.694E-03
                         3590    2990    2692    2504    2370    2677    2875    3078
                         1161    1026     964     927     901     886     883    2478
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                    690    669    658    651    645    640    638   2047
                    584    578    575    572    571    569    568   1777
                    552    551    550    550    549    549    549   1592
                    549    548    548    548    547    547    547   1454
                                                                    1060
                                                                     860
WTLOSSRATEIS 9.7374E-04LBS/SECANDTOTALWTLOSSIS   1.0924E-03LBSANDNOSERADIS 2.7088E-02FT
QSTARIS 0.        BTU/LB
                   6400   5978   4854   3931   3181   2591   2135   1830   1620   1464   1343   1248   1172
                   1108   1055   1009    969    935    906    881    859    840    823    808    795    783
                    773    764    756    749    743    738    734    730    728    726    691

 3.0000000E+01   1.9415298E+02   4.1937260E+05   6.3437662E+04   6.7638309E+04  -2.5561643E+01   6.2782796E+00
                 4.5493393E-02   1.5154919E+04   1.7967425E+04   1.5647826E+01   3.3701085E-02   6.0622161E+07
                 1.1555821E+02  -6.3148071E-02   4.6528959E-03   1.0414372E-01   1.8848454E+02   4.6528959E-03
                 1.7632097E+07   1.8367024E+05   1.1358009E+07   6.5455272E+02   3.0725785E+00  -3.6718282E+00
                 3.2786897E+01  -1.0690318E+02   5.5509858E+03   4.9020732E+05   5.1000000E-01   2.3080000E+01
   1.469E-02 1.435E-03 4.088E-03 1.347E-02 1.220E+08
1.566E-04 2.969E-07 1.289E+01 5.695E+02 4.284E-04 1.509E+04 4.597E-05 4.187E+02
 SDOT   0.         0.         0.         0.         0.         0.         0.         0.         8.742E-03
                   3864   3216   2893   2686   3246   3553   3676   3378
                   1232   1080   1009    966    948    948    951   2708
                    702    678    667    659    653    649    647   2216
                    588    581    578    575    573    572    571   1890
                    553    552    551    550    550    550    550   1671
                    550    549    549    548    548    548    548   1511
                                                                    1060
                                                                     860
WTLOSSRATEIS 9.6317E-04LBS/SECANDTOTALWTLOSSIS   2.5854E-03LBSANDNOSERADIS 3.0470E-02FT
QSTARIS 0.        BTU/LB
                   6400   6400   5156   4176   3394   2767   2281   1935   1698   1526   1394   1290   1208
                   1140   1082   1034    992    955    924    898    874    854    836    820    807    794
                    784    774    766    759    752    747    743    739    737    735    699

 3.1000000E+01   2.0650734E+02   4.3299196E+05   5.6907058E+04   6.1386296E+04  -2.5673637E+01   6.2782652E+00
                 5.4745747E-02   1.5048256E+04   2.3907315E+04   1.5537694E+01   3.2987327E-02   8.1484728E+07
                 1.1583447E+02   3.2928606E-01  -1.6381869E-01  -2.7816731E-01   1.9476779E+02   1.6381869E-01
                 1.7633530E+07   1.8962960E+05   1.1344205E+07   8.5154908E+02  -1.4378213E+02  -4.6514248E+00
                 3.2752972E+01  -1.0688387E+02   5.6710814E+03   5.0638062E+05   5.1000000E-01   2.3080000E+01
   1.471E-02 1.696E-03 4.146E-03 1.222E-02 1.504E+08
2.111E-04 2.969E-07 1.283E+01 5.673E+02 5.560E-04 1.498E+04 4.722E-05 5.412E+02
 SDOT   0.         0.         0.         0.         0.         0.         0.         0.         1.031E-02
                   4148   3452   3102   3802   4166   4356   4430   4055
                   1311   1140   1059   1028   1030   1041   1045   3008
                    715    689    676    668    663    659    656   2412
                    592    585    581    578    576    575    574   2014
                    554    553    552    551    551    550    550   1755
                    551    550    549    549    548    548    548   1571
                                                                    1060
                                                                     860
WTLOSSRATEIS 1.3771E-03LBS/SECANDTOTALWTLOSSIS   3.0498E-03LBSANDNOSERADIS 3.3143E-02FT
QSTARIS 0.        BTU/LB
                   6400   6400   5557   4481   3631   2957   2438   2044   1780   1591   1447   1334   1245
                   1172   1111   1059   1015    976    943    914    890    868    850    833    819    806
                    794    785    776    768    762    757    752    748    746    744    707
   TIME            X                Y                Z                ALT              GAMMA            VMAS
                   PSI.             VEL              QD               AMACH            CD               REN
                   PHI              THETA            ALPHA            BET              PS               ALPT
                   XF               YE               ZE               FD               FN               GFZ
                   LAT              LONG             BETA             GCIR             IZ               IX
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3.2000000E+01   2.1916943E+02   4.4648801E+05   5.0404296E+04   5.5168526E+04  -2.5782704E+01   6.2782479E+00
                5.7901008E-02   1.4907094E+04   3.1579669E+04   1.5391940E+01   3.2028597E-02   1.0920181E+08
                1.1577876E+02   8.3928392E-02   3.6701442E-03  -3.1833118E-02   2.0105108E+02   3.6701442E-03
                1.7634924E+07   1.9553462E+05   1.1330507E+07   1.0921373E+03   4.2550177E+00  -5.8416131E+00
                3.2719328E+01  -1.0686473E+02   5.8408212E+03   5.2242198E+05   5.1000000E-01   2.3080000E+01
  1.473E-02 2.038E-03 4.225E-03 1.103E-02 2.047E+08
2.842E-04 2.969E-07 1.274E+01 5.644E+02 7.191E-04 1.484E+04 4.952E-05 6.965E+02
   SDOT   0.        0.        0.        0.        0.        0.        0.        0.        1.220E-02
                     4446   3694   4222   4804   5029   5138   5175   5074
                     1401   1206   1132   1136   1153   1172   1182   3715
                      729    700    686    678    673    670    668   2808
                      596    588    584    581    579    578    577   2224
                      556    554    553    552    552    551    551   1070
                      552    550    550    549    549    549    549   1643
                                                                     1060
                                                                      860
   WTLOSSRATEIS 2.1239E-03LBS/SECANDTOTALWTLOSSIS   3.6074E-03LBSANDNOSERADIS 3.6353E-02FT
   QSTARIS 0.       BTU/LB
                     6400   6400   5947   4800   3889   3166   2603   2166   1868   1659   1503   1380   1283
                     1205   1140   1085   1038    997    962    932    906    883    863    846    831    817
                      806    795    786    778    772    766    761    758    755    753    716

3.3000000E+01   2.3200755E+02   4.5982552E+05   4.3946687E+04   4.9001293E+04  -2.5891421E+01   6.2781990E+00
                5.8101429E-02   1.4721629E+04   4.1364030E+04   1.5200439E+01   3.1563017E-02   1.4570261E+08
                1.1585339E+02   2.6566337E-02   3.8380305E-02   2.5293530E-02   2.0733441E+02   3.8380305E-02
                1.7636276E+07   2.0136999E+05   1.1316953E+07   1.4097208E+03   5.8283006E+01  -7.4150638E+00
                3.2686055E+01  -1.0684583E+02   5.9269317E+03   5.3828916E+05   5.1000000E-01   2.3080000E+01
  1.476E-02 2.512E-03 4.332E-03 9.917E-03 2.631E+08
3.817E-04 2.969E-07 1.262E+01 5.606E+02 9.259E-04 1.466E+04 5.092E-05 8.908E+02
   SDOT   0.        0.        0.        0.        0.        0.        0.        0.        1.752E-02
                     4747   4159   5384   5730   5849   5894   5901   5786
                     1501   1279   1262   1293   1320   1342   1352   4318
                      745    713    698    691    687    685    684   3263
                      601    592    588    585    583    581    580   2534
                      557    555    554    553    553    552    552   2039
                      553    551    551    550    550    549    549   1740
                                                                     1060
                                                                      860
   WTLOSSRATEIS 2.2213E-03LBS/SECANDTOTALWTLOSSIS   5.1812E-03LBSANDNOSERADIS 4.0316E-02FT
   QSTARIS 0.       BTU/LB
                     6400   6400   6400   5174   4167   3388   2777   2306   1967   1732   1561   1428   1323
                     1239   1170   1112   1062   1019    982    950    922    896    877    859    843    829
                      817    806    797    788    781    776    771    767    764    762    725

3.4000000E+01   2.4497912E+02   4.7295956E+05   3.7556386E+04   4.2905430E+04  -2.6001686E+01   6.2781758E+00
                5.8331901E-02   1.4400170E+04   5.3572294E+04   1.4951131E+01   3.1170063E-02   1.9291094E+08
                1.1596520E+02   2.2035493E-02   3.6884319E-02   3.0004922E-02   2.1361776E+02   3.6884319E-02
                1.7637582E+07   2.0711604E+05   1.1303589E+07   1.8030579E+03   7.2542527E+01  -9.3641090E+00
                3.2653266E+01  -1.0682721E+02   6.0016335E+03   5.5392817E+05   5.1000000E-01   2.3080000E+01
  1.480E-02 2.959E-03 4.478E-03 8.893E-03 3.351E+08
5.110E-04 2.969E-07 1.247E+01 5.558E+02 1.185E-03 1.442E+04 5.201E-05 1.130E+03
   SDOT   0.        0.        0.        0.        0.        0.        0.        1.148E-05   1.955E-02
                     5044   5665   6386   6566   6605   6602   6587   6400
                     1613   1409   1452   1498   1528   1550   1560   4867
                      763    727    714    708    705    703    702   3710
                      606    597    592    589    587    585    584   2859
                      558    556    555    554    553    553    553   2258
                      554    552    551    551    550    550    550   1860
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                                                                                1060
                                                                                 860
WTLOSSRATEIS 5.6249E-03LBS/SECANDTOTALWTLOSSIS   5.9280E-03LBSANDNOSERADIS 4.3532E-02FT
QSTARIS 6.2528E+03BTU/LB
                       6400   6400   6400   5660   4521   3650   2975   2462   2072   1811   1622   1479   1365
                       1275   1201   1139   1087   1042   1002    968    939    914    892    873    856    841
                        828    817    807    799    791    785    780    776    773    771    733

  3.5000000E+01    2.5801741E+02    4.8583481E+05    3.1260808E+04    3.6906678E+04    -2.6114147E+01    6.2421419E+00
                   5.8779700E-02    1.4172297E+04    6.8392552E+04    1.4633244E+01     3.0227403E-02    2.5000087E+08
                   1.1609253E+02    3.3366191E-02    2.1895502E-02    1.9185201E-02     2.1990112E+02    2.1895502E-02
                   1.7638836E+07    2.1274858E+05    1.1290469E+07    2.2252712E+03     5.4804465E+01   -1.1514961E+01
                   3.3621099E+01   -1.0680897E+02    6.1753212E+03    5.6927256E+05     5.1000000E-01    2.3080000E+01
   1.485E-02 2.488E-03 4.674E-03 8.190E-03 4.171E+08
6.810E-04 2.969E-07 1.227E+01 5.498E+02 1.505E-03 1.411E+04 5.318E-05 1.419E+03
  SDOT    0.        1.573E-04   9.693E-04   1.121E-03   1.130E-03   1.080E-03   9.860E-04   4.148E-04   2.234E-02
                       5324   6760   6760   6760   6760   6760   6760   6400
                       1735   1651   2100   2261   2321   2333   2298   5200
                        782    744    737    735    733    732    730   4077
                        612    601    596    593    591    590    589   3181
                        560    557    556    555    555    554    554   2507
                        555    553    552    552    551    551    551   2014
                                                                      1060
                                                                       860
WTLOSSRATEIS 1.4796E+00LBS/SECANDTOTALWTLOSSIS   1.1653E+00LBSANDNOSERADIS 3.9515E-02FT
QSTARIS 5.8218E+03BTU/LB
                       6400   6400   6400   6182   4918   3950   3204   2634   2198   1899   1689   1532   1410
                       1312   1233   1167   1112   1064   1023    987    956    930    906    886    869    853
                        840    828    818    809    801    795    790    786    782    780    742

  3.6000000E+01    2.7104423E+02    4.9839173E+05    2.5089733E+04    3.1032908E+04    -2.6230124E+01    6.1844773E+00
                   6.0004137E-02    1.3801142E+04    8.1666356E+04    1.3954017E+01     2.9191509E-02    2.8949270E+08
                   1.1622653E+02    5.0087543E-02    3.7060172E-03    3.7001607E-03     2.2618448E+02    3.7060172E-03
                   1.7640033E+07    2.1824158E+05    1.1277657E+07    2.5535016E+03     1.1022140E+01   -1.3268859E+01
                   3.2589705E+01   -1.0679118E+02    6.3667841E+03    5.8425059E+05     5.1000000E-01    2.3080000E+01
   1.497E-02 1.199E-03 5.140E-03 7.880E-03 4.700E+08
8.575E-04 3.078E-07 1.184E+01 5.573E+02 1.796E-03 1.374E+04 5.253E-05 1.717E+03
  SDOT    0.        2.092E-03   2.702E-03   2.745E-03   2.673E-03   2.559E-03   2.428E-03   1.215E-03   2.868E-02
                       5568   6760   6760   6760   6760   6760   6760   6400
                       1866   2735   3266   3409   3439   3421   3362   5456
                        803    780    789    793    793    792    789   4358
                        618    607    602    600    598    596    595   3454
                        561    559    557    556    556    555    555   2731
                        556    554    553    552    552    552    551   2178
                                                                      1060
                                                                       860
WTLOSSRATEIS 1.5392E+00LBS/SECANDTOTALWTLOSSIS   3.0206E+00LBSANDNOSERADIS 2.6956E-02FT
QSTARIS 5.4828E+03BTU/LB
                       6400   6400   6400   6400   5657   4390   3495   2835   2348   2001   1762   1590   1457
                       1351   1266   1196   1138   1088   1044   1007    974    946    922    900    882    866
                        852    839    829    819    812    805    800    795    792    789    751

  3.7000000E+01    2.8398555E+02    5.1057803E+05    1.9069685E+04    2.5308779E+04    -2.6349855E+01    6.1251836E+00
                   6.1514541E-02    1.3373414E+04    9.4332156E+04    1.3206643E+01     2.8715926E-02    3.2350201E+08
                   1.1634840E+02    5.3939236E-02    1.5451962E-03    1.1685716E-03     2.3246784E+02    1.5451962E-03
                   1.7641169E+07    2.2357218E+05    1.1265206E+07    2.8866867E+03     5.2812823E+00   -1.5084538E+01
                   3.2559215E+01   -1.0677391E+02    6.4431403E+03    5.9879891E+05     5.1000000E-01    2.3080000E+01
   1.511E-02 2.456E-04 5.739E-03 7.620E-03 5.067E+08
1.055E-03 3.199E-07 1.135E+01 5.718E+02 2.090E-03 1.332E+04 5.183E-05 2.050E+03
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SDOT    0.          4.048E-03   4.485E-03   4.423E-03   4.270E-03   4.091E-03   3.920E-03   2.274E-03   3.682E-02
                         6527     6760     6760     6760     6760     6760     6760     6400
                         2016     4168     4705     4770     4733     4658     4562     5711
                          826      859      892      901      901      897      890     4610
                          625      615      611      609      608      606      605     3692
                          563      560      559      558      557      557      556     2930
                          557      555      554      553      553      552      552     2344
                                                                                      1060
                                                                                       860
WTLOSSRATEIS 1.5841E+00LBS/SECANDTOTALWTLOSSIS    4.9283E+00LBSANDNOSERADIS 1.1750E-02FT
QSTARIS 5.1062E+03BTU/LB
                         6400     6400     6400     6400     6400     5305     3969     3122     2542     2121     1847     1653     1508
                         1393     1301     1227     1164     1112     1066     1027      993      963      937      915      895      873
                          864      851      840      830      822      815      809      805      801      799      760

   3.8000000E+01     2.9676008E+02     5.2234110E+05     1.3227627E+04     1.9759276E+04    -2.6473744E+01     6.0598707E+00
                     6.2918260E-02     1.2883235E+04     1.0604634E+05     1.2441658E+01     2.8970519E-02     3.5727562E+08
                     1.1647367E+02     5.6303680E-02     1.5104770E-04     1.5421329E-05     2.3875120E+02     1.5104770E-04
                     1.7642240E+07     2.2871740E+05     1.1253169E+07     3.2564899E+03     5.7727999E-01    -1.7138941E+01
                     3.2529764E+01    -1.0675725E+02     6.3526840E+03     6.1285368E+05     5.1000000E-01     2.3080000E+01
    1.527E-02 8.046E-06 6.466E-03 7.225E-03 5.450E+08
1.278E-03 3.317E-07 1.082E+01 5.844E+02 2.416E-03 1.283E+04 5.104E-05 2.423E+03
SDOT    1.926E-03   6.052E-03   6.362E-03   6.189E-03   5.947E-03   5.694E-03   5.478E-03   3.576E-03   5.525E-02
                         6760     6760     6760     6760     6760     6760     6760     6400
                         2844     5924     6251     6192     6075     5941     5814     5969
                          861     1018     1078     1086     1081     1070     1056     4853
                          632      625      623      622      620      619      617     3915
                          565      562      561      560      559      558      558     3137
                          559      556      555      555      554      554      553     2509
                                                                                      1060
                                                                                       860
WTLOSSRATEIS 1.7811E+00LBS/SECANDTOTALWTLOSSIS    7.0297E+00LBSANDNOSERADIS 2.1767E-03FT
QSTARIS 4.6876E+03BTU/LB
                         6400     6400     6400     6400     6400     6400     6400     4861     3065     2347     1965     1731     1566
                         1439     1339     1259     1192     1136     1089     1047     1011      980      953      929      909      891
                          876      862      851      841      832      825      819      815      811      808      769

   3.9000000E+01     3.0927702E+02     5.3362208E+05     7.5939767E+03     1.4412572E+04    -2.6602781E+01     5.9581510E+00
                     6.4244437E-02     1.3320872E+04     1.1577007E+05     1.1070721E+01     3.0400057E-02     3.9196982E+08
                     1.1660274E+02     5.7403778E-02     1.1241357E-04     3.8193064E-05     2.4503456E+02     1.1241357E-04
                     1.7643242E+07     2.3365151E+05     1.1241608E+07     3.7093165E+03     4.6635557E-01    -1.9754259E+01
                     3.2501501E+01    -1.0674127E+02     5.9964422E+03     6.2634340E+05     5.1000000E-01     2.3080000E+01
    1.546E-02 3.463E-06 7.373E-03 7.563E-03 5.863E+08
1.525E-03 3.431E-07 1.026E+01 5.950E+02 2.771E-03 1.227E+04 5.016E-05 2.829E+03
SDOT    4.157E-03   9.260E-03   9.357E-03   9.147E-03   8.825E-03   8.608E-03   7.135E-03   5.134E-03   8.955E-02
                         6760     6760     6760     6760     6760     6760     6760     6400
                         4242     6760     6760     6760     6760     6760     6680     6206
                          939     1585     1725     1642     1473     1344     1287     5085
                          641      642      643      640      637      635      633     4129
                          567      564      563      562      561      561      560     3326
                          560      558      557      556      555      555      555     2659
                                                                                      1060
                                                                                       860
WTLOSSRATEIS 1.5396E+00LBS/SECANDTOTALWTLOSSIS    1.0302E+01LBSANDNOSERADIS 1.4320E-03FT
QSTARIS 4.2251E+03BTU/LB
                         6400     6400     6400     6400     6400     6400     6400     6400     6400     6400     6400     4104     2033
                         1587     1409     1302     1225     1163     1112     1068     1031      998      969      944      923      904
                          888      874      862      852      843      836      829      824      821      818      778
   TIME                 X                   Y                   Z                   ALT                 GAMMA               VMAS
                        PSI.                VEL                 QD                  AMACH               CO                  REN
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            PHI           THETA          ALPHA          BET            PS             ALPT
            XE            YE             ZE             FD             FN             GFZ
            LAT           LONG           BETA           OCIR           IZ             IX

4.0000000E+01  3.2142579E+02  5.4434838E+05  2.2063965E+03  9.3036353E+03  -2.6738445E+01  5.8963068E+00
               6.5550739E-02  1.1675938E+04  1.2232342E+05  1.0825397E+01   3.1673323E+02  4.2669005E+08
               1.1673848E+02  5.8540495E-02  4.1042428E-05  5.1103690E-07   2.5131792E+02  4.1042428E-05
               1.7644169E+07  2.3834279E+05  1.1230599E+07  4.0485423E+03   1.7836803E-01 -2.1781031E+01
               3.2474610E+01 -1.0672608E+02  5.7342915E+03  6.3917992E+05   5.1000000E-01  2.3080000E+01
   1.568E-02 1.004E-04 8.540E-03 7.349E-03 6.284E+08
1.795E-03 3.539E-07 9.658E+00 6.034E+02 3.145E-03 1.163E+04 4.920E-05 3.257E+03
  SDOT    6.317E-03    1.095E-02    1.089E-02    1.057E-02    1.017E-02    9.889E-03    9.589E-03    8.852E-03    1.117E-01
                 6760      6760     6760     6760     6760     6760     6760     6400
                 6089      6760     6760     6760     6760     6760     6760     6400
                 1102      2811     2915     2772     2543     2379     2182     5343
                  652       684      688      682      673      667      661     4350
                  569       567      566      565      564      564      563     3511
                  562       559      558      557      557      556      556     2805
                                                                                  1060
                                                                                   860
WTLOSSRATEIS 1.3126E+00LBS/SECANDTOTALWTLOSSIS   1.2292E+01LBSANDNOSERADIS 8.0814E-03FT
OSTARIS 3.7186E+03BTU/LB
                 6400      6400     6400     6400     6400     6400     6400     6400     6400     6400     6400     6400     6400
                 6400      3165     1839     1449     1274     1175     1108     1059     1020      988      961      938      918
                  901       886      874      863      854      846      840      835      831      828      788

4.1000000E+01  3.3310703E+02  5.5446108E+05 -2.9038547E+03  4.4612753E+03  -2.6802263E+01  5.8435952E+00
               6.6822230E-02  1.0975483E+04  1.2540935E+05  9.9011585E+00   3.3183417E-02  4.5555993E+08
               1.1688229E+02  5.9598032E-02  5.1427385E-05  2.7626110E-06   2.5760128E+02  5.1427385E-05
               1.7645017E+07  2.4276550E+05  1.1220202E+07  4.3322374E+03   2.2827824E-01 -2.3466699E+01
               3.2449241E+01 -1.0671176E+02  5.4491358E+03  6.5129131E+05   5.1000000E-01  2.3080000E+01
   1.594E-02 2.791E-04 1.003E-02 6.934E-03 6.629E+08
2.082E-03 3.642E-07 9.025E+00 6.103E+02 3.533E-03 1.093E+04 4.822E-05 3.700E+03
  SDOT    9.461E-03    1.243E-02    1.223E-02    1.182E-02    1.134E-02    1.100E-02    1.066E-02    9.031E-03    1.206E-01
                 6760      6760     6760     6760     6760     6760     6760     6400
                 6760      6760     6760     6760     6760     6760     6760     6400
                 1791      4230     4232     3996     3688     3475     3241     5480
                  670       773      779      766      747      734      720     4525
                  572       573      572      571      569      568      567     3681
                  564       562      561      560      559      558      558     2951
                                                                                  1060
                                                                                   860
WTLOSSRATEIS 1.0871E+00LBS/SECANDTOTALWTLOSSIS   1.3827E+01LBSANDNOSERADIS 1.3385E-02FT
OSTARIS 3.2808E+03BTU/LB
                 6400      6400     6400     6400     6400     6400     6400     6400     6400     6400     6400     6400     6400
                 6400      6400     3874     2266     1634     1370     1226     1136     1072     1025      988      959      936
                  916       900      886      875      865      857      850      845      841      838      797

4.1980000E+01  3.4401700E+02  5.6373240E+05 -7.6188187E+03 -3.6507869E+00  -2.7032821E+01  5.8125682E+00
               6.8030337E-02  1.0246162E+04  1.2480186E+05  9.1736265E+00   3.4757131E-02  4.6840857E+08
               1.1703284E+02  6.0593998E-02  6.0893490E-05 -4.4316915E-06   2.6375898E+02  6.0893490E-05
               1.7645770E+07  2.4682006E+05  1.1210553E+07  4.5025148E+03   2.6820138E-01 -2.4523572E+01
               3.2425969E+01 -1.0669863E+02  5.1851546E+03  6.6740303E+05   5.1000000E-01  2.3080000E+01
   1.624E-02 9.374E-05 1.189E-02 6.529E-03 6.751E+08
2.378E-03 3.737E-07 8.303E+00 6.157E+02 3.920E-03 1.020E+04 4.692E-05 4.141E+03
  SDOT    1.078E-02    1.366E-02    1.335E-02    1.283E-02    1.227E-02    1.187E-02    1.149E-02    9.035E-03    1.301E-01
                 6760      6760     6760     6760     6760     6760     6760     6400
                 6760      6760     6760     6760     6760     6760     6760     6246
                 2967      5584     5460     5146     4777     4519     4255     5501
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                  716     929     931     901     865     840     816    4631
                  576     583     582     580     578     576     575    3814
                  566     565     564     563     562     561     561    3081
                                                                         1060
                                                                          860
WTLOSSRATEIS 8.1076E-01LBS/SECANDTOTALWTLOSSIS   1.4983E+01LBSANDNOSERADIS 7.463AE-03FT
QSTARIS 3.2275E+03BTU/LB
                 6400    6400    6400    6400    6400    6400    6400    6400    6400    6400    6400    6400    6400
                 6400    6400    6400    4220    2481    1739    1436    1268    1163    1090    1037     996     964
                  939     919     902     889     878     869     861     856     851     848     807
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13. ABSTRACT

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An integrated computer program (STRAB-6) for the complete analysis of a blunt, conical reentry vehicle as to its trajectory and aerothermal environment upon atmospheric reentry is presented. The trajectory portion of the program calculates the vehicle motions in six-degrees-of-freedom, while the thermal portion calculates the aerodynamic heating and ablation of the vehicle. The earth model is an oblate, rotating spheroid whose parameters and gravitational potential are described herein. The equations of motion, the method of integration, thermal model and input forms for the program are discussed. The thermal model examined in this report assumes thick skin solution where the skin is of any composite structure made of discrete layers of material whose properties may vary from layer to layer. Also, the heatshield is comprised of one, two, or more different ablative materials. STRAB-6 computes nose-blunting and includes this effect in the aerodynamics. STRAB-6 is written in FORTRAN IV for the CDC 6600 computer.

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